T H E S I S

O N T H E

I N T R A C R A N I A L C I R C U L A T I O N

IN THE CLOSED AND IN THE UNCLOSED SKULL

WITH

special reference to the question of the movements of the cerebro-spinal fluid under ordinary physiological conditions.

B Y

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INTRODUCTION.

The remarkable functions performed by the brain and the great readiness with which these functions are, under many conditions, interfered with, have naturally led to a large amount of discussion and investigation as to the circulation inside the skull and the means by which the cerebral tissue receives its nourishment. The inherent difficulty of such investigations, from the presence of the cranium surrounding the brain on all sides, has not lessened the amount of discussion on the question, for theories frequently enough based on but scanty facts have been rife for the last century and a half. The result of this has been, that the literature on the subject, though extremely voluminous, is very confusing.

Scope of Thesis.

The present thesis does not pretend to deal with the whole or even a large part of this great question, but is specially directed towards a discussion of the pecularities of the intracranial circulation under ordinary physiological conditions, although some pathological aspects will also be touched on more or less briefly.

The writer has found much difficulty in determining what order to take up the various aspects of the question he wishes to present and has eventually decided on that which follows, viz:-

1st. A consideration of the changes in the circulation inside the skull as they can be determined by observation of the movements of the brain, in the human subject as well as in the lower animals, where the cranium is not intact.

Subjects to be discussed

2nd. A resumé of the chief work and writings on the subject of the circulation inside the cranium. This is practically necessary for the discussion of the

3rd. portion. A consideration of the question of the intracranial circulation inside the closed skull. And

4th. Some references to pathological conditions which are closely associated with the questions raised in the 1st and 3rd parts will be considered.

At first sight it seems rather out of place for the discussion of the intracranial circulation in the unclosed skull to come before the historical resumé of the literature on the subject, but after careful consideration the writer found that in many ways it was preferable to take up the divisions in the order he has adopted.

I. THE INTRACRANIAL CIRCULATION IN THE UNCLOSED SKULL.

As might be expected nearly all our information regarding the circulation inside the closed skull has been derived from the observation of those cases where, through injury or disease, part of the calvarium has been lost and where, accordingly, the exposed brain and membranes are directly under the observation of the investigator. Such cases are not very common in the human subject and so naturally much work has also been done by laying bare the brain and membranes in animals experimentally. In all such cases movements of the brain are usually visible and these movements have been observed from a very early period in medical history, and about the middle of last century attracted much attention.

Most of the information regarding intracranial circulation has been got from observation of movements in the unclosed skul

Whilst a large amount of information regarding the circulation of the brain was acquired from a simple observation of these brain movements, it is within the last 20 years (after the introduction of the Graphic method of recording movements) that most of the advance in the investigation of these movements has taken place.

It is remarkable, however, that nearly all the work has been done an adults with gaps in the skull from some cause, or in animals which have been trephined under an anaesthetic In the fontanelle of the child, there is to hand an opportunity of investigating these movements, which can be taken advantage of by any one at any time. Very little advantage has been taken of this so far apparently, though Salathé and others have published tracings of the fontanelle movement along with their other tracings of brain movement.

Fontanelles of children have been little made use of.

During the summer of 1894 when acting as Resident Physician to the Royal Hospital for Sick Children, the writer had the opportunity of taking a large number of tracings of the fontanelle movements in children. A few of these were reproduced, and some deductions to be made from them appeared, in the Edinburgh Hospital Reports of 1895 (70). In children, however, the obvious difficulty of course is to get the child to remain at rest for a sufficient length of time, for few children when awake will remain quiet whilst the tracings are being taken, and even when observations are begun on children when they are asleep the noise of the instrument used usually rouses them. Therefore, there are distinct drawbacks to using the fontanelle of children as

Present observations were made on (a) children with fontanelle still open.

the means of obtaining records of brain movement.

(b) girl with persistent fontanelle.

Since then the writer has had the opportunity, through the kindness of Dr Lockhart Gillespie, of making some observations on a girl of about 9 years, whose fontanelle has remained unclosed. Although the membrane of the fontanelle is rather firm, and the movements consequently not very ample, some of the tracings obtained were extremely satisfactory. The girl, though deaf and dumb (3 others of the same family are also deaf and dumb), was very intelligent and behaved very well indeed when the tracings were being taken. One of the teachers of Donaldson's Hospital, where she is, was present to give her instructions what to do when required.

The tracings subsequently shewn are partly those of children's fontanelle's and partly those taken of the movement of this girl's brain.

Methods used in making these observations.

The apparatus used both in the case of the children and also of the girl consisted of chiefly,(1) the ordinary Marey's sphygmograph applied to the fontanelle. This gave very good tracings indeed, but of course they were short. When longer tracings were required the movements were recorded by (2) a cardiograph, the button of one tambour being fixed over the fontanelle by a bandage so that it would not move, whilst the lever of the other tambour wrote on a revolving cylinder. Often the movements are rather fine and it was found necessary, in many cases in order to obtain satisfactory tracings, to get specially fine tambours and levers made. To record the respiratory movements synchronously with the fontanelle movement (3) a large tambour was used, kept convex by a spring inside. This was applied to the epigastrium, so that it did not move and then required no further attention. A tambour with lever on it, in connection with this wrote on the revolving cylinder.

A modified Dudgeon's sphygmograph and a Mackenzie's polygraph were also used, but were found to be not nearly so satisfactory as the cardiograph and the sphygmograph of Marey.

Two chief sets of brain movement.

In practically all tracings of the brain movements, two chief sets of movements are seen, viz., the arterial and the respiratory.

i. Arterial movement.

i. The arterial movement. The pulse, as shewn by a fontanelle tracing, is comparable in most particulars to the arterial pulsation in the radial or any other artery. It varies greatly in different individuals and varies in form according to the tension - being, as a rule, high and sharp where the tension is low, and lower and more prolonged (rounded) where the tension is high. One must remember, however, that in dealing with the fontanelle pulse one has to take into consideration the whole intracranial tension, not merely the intra-arterial tension as in the ordinary arterial pulse, and this intracranial tension, as will be discussed later on, does not depend altogether, and probably not even chiefly, on the intra-arterial tension.

Brain pulse is usually anacrotic.

In the large majority of cases, too, we found that the pulse was anacrotic in character, see figs. 1, 2, 3, 6, 9, etc. This peculiarity of the cerebral pulse was first described by Mosso (37) who shewed that the pulse was what he called "tricrotic" or "tricuspidal," and that as a rule the middle one of the three cusps was the highest, the pulse being then anacrotic, although not uncommonly the first was the highest forming a katacrotic pulse. Salathé (31) although most of his tracings, which are large enough shew the anacrotic character or at least a rounded apex, does not refer to this peculiarity; whilst François-Franck and Pitres (42) are inclined to think that Mosso has laid too great an importance on this point. Most recent writers on the subject, however, have observed this anacrotic form of pulse, and some discussion has arisen as to its causation, although so far no satisfactory answer has been given.

Theories as to cause of the anacrotic form of the brain pulse.

Fredericq (39) thinks that the anacrotic pulse is auricular, i.e. that from the right auricle there is transmitted to the brain through the jugular veins a pulsation, which is the cause of the "doubling of the summit," one cusp being the ordinary arterial wave, another this venous wave already referred to, whilst the last is the ordinary dicrotic wave.

He seems to have proved that in dogs (on which he made experiments) a venous wave may reach the brain, but this is far from proving that the anacrotic pulse got in brain tracings is the result of this wave. It is difficult to imagine that the transmission of a wave from the auricle through the veins should be so regular, as regards the time taken for it to reach the brain, as to bear a constant and definite relation to the arterial pulse - if we remember that at different periods of the respiratory act (as will be shewn later), the blood flow along the veins from the cranium varies very greatly. At one time the preliminary expansion before the chief wave of the pulse was supposed to be due to a transmitted pulsation from the vessels at the base of the brain, but from experiments timing the pulsation of the brain with that of the carotid high up (Tietze (51) etc.) this has been declared, as was to be expected, not to be possible.

The fact that the anacrotic form of pulse has been got in tracings by very various instruments-

(in our own tracings as distinctly by the sphygmograph as by the cardiograph) seems to shew that it is not produced by the method of transmission of the wave to the recording surface.

It is important to remember that in many tracings of a large part of an extremity as taken by a plethysmograph the pulse is also anacrotic, and Mosso (37) is inclined to believe that the anacrotic is the normal form of pulse wave for any considerable section of the body; and attention has been drawn to the great resemblance between the conditions in these two cases - the cranium being compared to the wall of the plethysmograph, the cerebro-spinal fluid to the contained water, and the fontanelle to the elastic membrane. In the tracings taken by the new instrument devised by Hallion and Comte (59) for taking the pulse of the hand, where there is no liquid, there is no anacrotic appearance, but here only two fingers are indicated in tne apparatus and according to Mosso it is only when a considerable part of the body is included that the pulse is anacrotic.

Certain it is, whether the means of conduction has any influence in the production of the anacrotic wave or not, that it is not due to an irregularity of the ventricular action, as has been suggested as the reason of the anacrotic character of the radial pulse in various conditions, else it would not be so universal.

Although most of our tracings were anacrotic they were not all so - some were katacrotic and some high and sharp without any distinct "cusps" on them at all. In these cases the fontanelle was lax and the intracranial pressure evidently low, see figures 4 and 5.

Brain pulse is not always anacrotic, however

It has been already said that with high intracranial pressure the pulse waves were low and rounded, that with low intracranial pressure the pulse waves were high and sharp. This, although usual, is by no means constant, for it has been shewn that in certain states of mental activity along with the rise of the intracranial pressure the individual pulsations were also more ample; and in the tracings taken of the fontanelle of the girl during the inhalation of amyl nitrite, the writer found that with rise of the level of the tracing there were also heightened pulsations. Fig. 33. Binet and Sollier (71) in a recent paper, state that with recession of the brain, i.e., with lowered intracranial pressure the individual pulsations are smaller, and they give tracings to shew this.

Change in form of brain pulse according to state of the intracranial pressure.

The tracings they shew are very small, however, and in view of the fact that their results seem to be opposed to those of other observers*, and from examination of them, one is inclined to think that with the recession of the brain their instrument did not properly follow the organ and so did not record its pulsations accurately.

ii. The respiratory movement.

ii. <u>The respiratory movement</u>. One of the most noticeable features about tracings of the fontanelle is the presence of undulations in the tracings synchronous with the respiratory movements, as seen in figures 1, 6, 8, etc., taken from children under normal conditions. They are also well seen in figs. 30 and 33 where child was under the influence of amyl nitrite and in fig. 28 where the child was deeply under chloroform.

In the tracings where the respiratory movements are given, it must be borne in mind that by the instrument used, the inspiratory act is represented by a rise in the tracing, and the expiratory act by a fall in the tracing; this of course is the reverse of the tracings given by the stethograph.

The fontanelle sinks with inspiration, and bulges with expiration.

In the figures referred to, it is readily seen that with inspiration there is a marked descent in the fontanelle tracing, whilst with expiration there is a corresponding rise. The descent of the fontanelle is often so distinct as to be readily distinguished by the hand placed on the head of the child.

The descent of the fontanelle with ~~re~~inspiration in ordinary breathing practically coincides with the movement, beginning at once and ending with the beginning of the expiratory movement. What is the cause of this descent of the fontanelle during inspiration.

Movements of the brain with respiration are produced through the venous system.

That the influence of respiration on the brain movements must be exercised through the venous system is evident, when we consider that soon after the beginning of inspiration the arterial pressure rises, the rise lasting into the beginning of the expiratory period. This curve does not in the least correspond with the movement of the brain during inspiration, indeed it is almost exactly diametrically opposed to it. And when we remember that during inspiration the veins of the neck are emptied and flattened, we would naturally expect a distinct depression of the brain in the unclosed skull at the same time. Professor McEwan of Glasgow (57) however, has comparatively recently suggested that such aspiratory action on the veins as the inspiratory movement has, only reaches the base of the skull; that where the sinuses of the brain leave the skull their shape

MacEwan's views.

is such that a reservoir is formed by means of which aspiration of the intracranial veins is prevented. This 'reservoir' is the sigmoid sinus, a schema of which he gives shewing how it acts and he adds that, if the aspiratory action reached as far as the veins in the brain, the result would be disastrous. That the depression of brain during inspiration is due to its action on the veins is shewn by the fact, that when the main veins are ligatured the movements cease, whilst they do not do so though most of the main arteries are; and if the sigmoid sinus were to act in the way described by MacEwan, the movement of the brain would not correspond so closely with that of inspiration. Besides it has been shewn by Mosso (37) who inserted a manometer into an intracranial sinus, filling up the gap in the skull with a firm plate, and by Bayliss and Hill (68), whose researches will be afterwards referred to, that such a direct influence on the intracranial sinuses by the respiratory movements is produced.

Arguments against them

Brissaud and François-Franck (32) (1877), suggested that the rise of intracranial pressure during effort and during expiration might be partly due to the fact that at these times more blood was sent from the aorta, the so-called "emptying of the aortic reservoir," but there cannot be the slightest doubt that these rises of pressure with accompanying lowering in the height of the individual pulse waves, are to be explained from the venous and not from the arterial side. The researches of Bayliss and Hill (68), prove this conclusively, if any proof were required beyond the facts already stated. The ordinary movements of the brain in the unclosed skull correspond to the variations in the venous pressure inside the cranium produced by the respiratory acts. When, during inspiration, blood is sucked from the intracranial veins, the intra-venous pressure falls to such an extent that the veins become compressed from the atmospheric pressure; on the other hand, during expiration the intra-venous pressure rises and the atmospheric pressure is not sufficient to cause this compression of the veins.

Movements of the brain do not always exactly coincide with the respiratory movements.

Whilst during ordinary fairly rapid respiration the movements of the brain correspond almost exactly with the respiratory movements, this synchronism is not kept when the respirations are irregular or somewhat prolonged. Thus when inspiration is prolonged, although at first there is a descent of the brain tracing, yet towards the end of inspiration the tracing rises again (see fig. 14) and the reason of this is evident, because after the chest has been kept in the position of inspiration for a certain time the space has become filled up by the lungs and, to a much lesser extent, by blood from the upper part of the body, and there is no longer a negative pressure inside the chest, consequently no longer an aspiration of the veins of the neck and skull: conversely with the expiratory movement when prolonged.

In none of our tracings taken fron the fontanelle could any difference in the rate of the pulse during inspiration and expiration be made out.

Binet and Sollier's views on the relation of the form of the brain pulse to the state of the intracranial pressure.

Binet and Sollier (71) in their article already referred to, give considerable prominence to the fact that, during inspiration the individual pulse waves in the tracings from the brain are smaller than during expiration, and say there is a 'constriction' (sic) produced at the beginning of inspiration in the vessels of the brain. In none of our tracings have we seen this, and by no others (Salathé (31), Fleming (33), etc.) has it been called attention to so far as we know, nor can one in tracings of other observers find any evidence of it. I have already referred to the fact that the tracings of Binet and Sollier are so small that they had to give schematic enlargements of them, and the apparatus would indeed require to be delicate which could be trusted when read very closely in this way. In some of these "schemata", however, the apparent difference in volume of the individual pulse waves is partly, at least, due to the general movement of the brain with respiration. Thus, during inspiration as the level of the tracings is falling, it naturally follows that the height of the pulse wave must be reckoned not from the depression before it began, but from a point about midway between the depression before it and the depression after it; and, similarly, the height of the expiratory wave must not be reckoned from the depression before it, but midway between it and the depression after it. If estimated from the depression before it, the inspiratory wave appears too low, the expiratory wave too high. Besides, in most cases of course each respiratory act does not exactly coincide in time with a definite number of pulse beats (say, not 3 pulse beats to 1 respiratory movement but $3\frac{1}{4}$), it is evident that the pulse waves vary in their position on the respiratory curves and consequently, vary to a certain extent in their apparent height. In some of the tracings, however, the pulse wave is apparently not so high during inspiration, and there is a considerable probability that this is due to the fact that, during inspiration the instrument they used did not follow quite completely the recession of the brain.

Probable explanation of their results.

The writer is, therefore, not inclined to accept without further evidence the proposition that during inspiration the pulse in the brain is smaller than during expiration, especially when we consider that, as a rule, as already shewn, the brain pulse waves during low intracranial tension are more ample than when the intracranial tension is high. One would naturally expect, therefore, that if there was any difference, that difference would be in an opposite direction to that described by them, viz: that during inspiration the pulse waves would be higher, and this is almost certainly the case.

During quiet respiration a fine apparatus is required to shew the respiratory undulations in the brain pulse.

Salathé (31), Brissaud, and Francois-Franck (32), and others state that, during quiet respiration there are no respiratory movements to be seen in tracings from the brain. In many of ours, the movements could not be seen, but in many others they could. The more quiet the respiratory movements the less influence have they on the brain movements, and it just depends on the delicacy of the apparatus as to what proportion of the tracings will shew the movements. We could get no very satisfactory results until we had ~~got~~ specially fine tambours (as in Mackenzie's polygraph) made for the purpose.

The intracranial tension undergoes changes under many other conditions than respiration, and we will now consider some of these.

A. Sleep. During sleep, we found that there was still usually present the anacrotic form of wave, and as a rule the respiratory movement could also be seen, see Fig. 9. Salathé (31) said that during sleep, respiration had no effect on the tracing from the brain, but, as already mentioned in speaking of quiet respiration, the question is merely one of whether the instrument used is delicate enough to shew the effect of the respirations when these are specially quiet,- as they are during sleep as a rule.

The brain pulse during sleep.

The whole intracranial pressure is also less during sleep, and immediately the patient awakes, the pressure is seen to rise. This is seen in Fig. 15 where a modified Dudgeon's sphygmograph was applied to a child's fontanelle and a tracing begun. Almost immediately, however, the child woke up and at once one got a sudden and marked rise of pressure, so that the lever left the paper. But whilst the whole intracranial pressure is low, the pulse waves are also small, no doubt from less active heart's action. The fact that the pulse waves were smaller during sleep led Fleming (33) to think that at that time there was congestion of the brain. But the tracings of Mosso (37) taken for long periods of time, conclusively prove that the intracranial pressure is less - in fact, that there is anaemia of the brain during

During sleep intracranial pressure is low.

Pulse waves are also small.

sleep. This does not, of course, mean that sleep is caused by the anaemia. It has also been shewn that during sleep apart from the changes in the level of the tracing from respiratory acts, snoring, etc., there are very marked rises of pressure from dreams, and when one makes a noise in a room where such a patient is, there is also a distinct rise although the patient is not wakened by the noise. (Mosso). This would seem to suggest a certain amount of activity in some of the sensory centres at least, during sleep.

Brain pressure rises when the patient awakes.

When a patient wakens, the brain pressure rises very distinctly, and the pulse waves become more ample, <u>vide</u> Figs. 9, and 10, and 12, and 13, This is interesting as differing from the general rule, that with higher intracranial pressure the pulse waves are less, and with lower intracranial pressure the pulse waves are more ample. The reason for this must be sought in a consideration of the two sides of the circulation in the brain. When the intracranial pressure is raised from the venous side, i.e., through rise of venous pressure due to some obstruction to venous outflow from the skull, or to rise in the general venous pressure, the general rule holds, i.e., the pulse waves are lower whilst the general level of the tracing rises; when, on the other hand, the

Distinction between 'active' and 'passive' rise of intracranial pressure.

rise of intracranial pressure is from the arterial side without obstruction of venous outflow, such as occurs evidently when a patient awakes and, as will be seen immediately, when mental processes are going on, with the rise in the general level of the tracing there is also an increase in the amplitude of the pulse waves. These may be called respectively a "passive" and an "active" rise of intracranial pressure.

As will be seen later on, however, the intracranial pressure responds much more readily and more frequently to alterations in the state of the venous pressure than to alterations in the state of the arterial, and that is why in the large majority of cases, rise in the intracranial pressure is accompanied by a lowering of the height of the individual pulse waves.

'Passive' rise much more frequent than 'active'.

B. Mental processes of various kinds. It is obviously impossible to investigate with any degree of satisfaction the effect of mental processes in children with open fontanelles, but the writer was able to observe such effects in the deaf and dumb girl with the open fontanelle. Such an effect is seen in Fig. 19. A continuous tracing of the fontanelle movement was being taken when at a, a piece of chocolate was shewn, and immediately there

Brain pulse during mental processes

was quite an appreciable rise in the tracing, which fell to its ordinary level when the cholocate was again taken away. (c) A similar rise occurred when she was shewn a penny. Fig. 31.

Mental activity of another kind was produced by giving a simple mental calculation in arithmetic. This always led to a distinct rise in the level of the tracing, which again fell after the answer was given. Such rises are seen in Figs. 16, 17, 18 & 20.

Intracranial pressure rises during mental activity.

Rises of the general level of the tracing were also seen when the patient was being told a story, or indeed when the mind was active in any way. Although the tracings here given are not fine enough to shew differences in the individual pulse waves, Mosso (37) has shewn that with rise in the general level of the tracing the individual pulse waves become higher, i.e., that an "active" distension of the brain occurs. Mosso, at the same time, took a hydro-sphygmographic tracing of the arm and found that, with nearly every rise of intracranial pressure, there was a diminution in the volume of the arm, i.e. that with the increased flow of blood to the brain there was an accompanying decrease in quantity of the blood in the limbs, and he has also shewn that with mental activity there is a rise in the general arterial tension. These are points of very great

Pulse waves also become higher and tend to become katacrotic.

importance in the consideration of the regulation of the blood supply of the brain, and will be discussed later on, in considering the question of vaso-motor supply to the brain. (page 111 etc.)

Effect of changes of attitude on brain pulse.

C. Change of attitude, has a very marked influence on the intracranial pressure. If the head is put forward or from side to side at once the intracranial pressure rises, and the pulse waves are less ample. This is well seen in Fig. 21, where a continuous tracing of the fontanelle movements in the girl with the open fontanelle was being taken. At a. the head was gently pushed forward and at once a marked rise in the fontanelle tracing was seen. A similar rise in the tracing occurs on pressure on veins of the neck, e.g., by a cord, and there is no doubt that the rise of pressure in such changes of attitude, as moving the head forward or from side to side, is chiefly due to obstruction to the venous outflow from the skull.

Decrease of intracranial pressure in the erect attitude.

If a tracing of a child's fontanelle is taken when the child us lying at rest, and then the child be gently raised, so that the head is erect, there is at once a marked decrease in the intracranial pressure; whether the child be asleep or awake.

The reason for this is obvious, for, the action of gravity causing a more rapid flow of blood to the thorax in the erect posture, there is a depression of the brain in the unclosed skull from decrease of the venous pressure. Here, again, with the decrease in intracranial pressure the pulse waves are higher. This is well shewn in Figs. 10 and 11, and if these be compared with Fig. 9,one will see that when the child was asleep the pulse waves were small, when it awoke and was still recumbent and at rest the pulse waves became higher, though the consequent rise of pressure (an "active" rise) is not shewn in the tracings (which were not continuous,being taken with the sphygmograph) whilst when child's head was propped up (the child being still perfectly quiet) the pulse waves became still higher, though now the intracranial pressure would become less (a "passive" fall) This is also seen in Fig. 5, taken when the child was erect. At the same time that the pressure falls and the pulse waves become higher, the waves alter in character also, becoming less rounded and losing to a large extent their anacrotic character. This will be readily seen also in Figs. 22 and 23; 22 being from a child in the recumbent posture and 23 when it was held sitting with the head erect. They were taken as the child was coming out of chloroform.

Pulse waves are also higher and sharper when head is raised.

When the limbs are held above the head, the intracranial pressure also rises due to an increased

Holding the arm above the head causes rise of intracranial pressure.

quantity of blood in the cranium, from derivation from the hand. Here also the pulse waves are smaller. This rise of tension from the raising of the arm above the head is well seen in the tracing Fig. 36., taken from the deaf and dumb girl with the open fontanelle. When the arm is lowered the tracing again falls.

Effects of movements on the brain pulse.

D. Movements. Speaking generally all kinds of movements cause an increase of intracranial pressure, partly by interfering with the free outflow of blood from the skull, either by the muscles pressing on the veins directly, or by the fixation of the chest produced, for when the chest is fixed even in the condition of full inspiration there is necessarily a rise of venous pressure in the veins of the neck from the negative pressure in the chest ceasing as soon as the inspiratory movement ceases. Partly also, no doubt, it is due to the rise in the general venous pressure produced by movements.

The rise of pressure, consequently, is like nearly all the others, a passive rise.

These results are shewn in Figs. 25 and 26., where rise of pressure was due to the general restlessness of the child.

Effects of sucking.

Sucking produces great alterations in the level of the tracing as a rule, evidently from the very irregular respiration of the child during that act. (Fig. 32.)

Crying is accompanied by a very distinct rise of intracranial pressure, the fontanelle being felt to bulge strongly when the hand is placed over it. (See Fig. 27.)

Effects of crying.

E. Anaesthesia. During the anaesthesia of chloroform the whole intracranial tension seems to be low, whilst the pulse waves are also low, so that the condition is very similar to that during sleep. The respiratory movements are usually very distinct, however, probably because as the brain is in a state of comparative anaemia the aspiration of blood during inspiration makes a greater impression on the quantity of blood inside the cranium than a similar aspiration would during ordinary circumstances, vide Figs. 28 and 29.

Effects of Anaesthesia.

Here, although the pulse waves are small and, owing to great respiratory movements, not so defined as in most of the other tracings, the tricuspid nature of the pulse is distinctly seen.

As the child comes out of chloroform the respiratory waves become distinctly less marked, Fig.29. this tracing of the same child, whose tracing is shewn in fig. 28. when deeply under chloroform, was taken as the child was coming out of its influence.

F. Nitrite of Amyl. It was naturally very difficult to get tracings shewing the effect of amyl nitrite on babies as they wakened up, became restless, and usually began to cry almost as soon as the capsule was held in front of them.

Effects of nitrite of amyl.

Some very good tracings were, however, got from the girl with the open fontanelle, and the results are particularly interesting from several points of view. Figs. 30 and 33.

Soon after inhalation began, the pulse rate increased considerably, and with this there was an expansion of the brain, as shewn by a rise in the general level of the tracing. At the same time, the individual pulse waves became enormously greater and also altered in character becoming distinctly katacrotic, with a very marked dicrotic wave, where before they had been anacrotic. The respiratory undulations were much more evident and this was not due apparently to the respiratory movements becoming greater, although they tended to become quicker, see Fig. 33.

The general rise of the tracing was evidently due to a dilatation of the small arteries of the brain, a point of great importance, as at the same time the small arteries throughout the body are also dilated. This is directly contrary to what usually

Arteries of the brain are dilated by amyl nitrite happens, for, as we have seen, with mental effort whilst the brain expands the vessels of the extremities contract and, on the other hand, when the vessels of the extremities dilate the brain is depressed. The further bearings of this will be referred to further on in the thesis, (page 114 etc)

Here, again, is a case where high pulsations accompany expansion of the brain - an "active" expansion in fact.

The form of the pulse wave after the inhalation of nitrite of amyl is also seen in Figs. 34 and 35, where the first part of fig. 34 was taken when the child was asleep. She wakened up when the nitrite of amyl was held in front of her, and 35 is the tracing when she was awake and under its influence.

G. Meals. In one of Mosso's (31) patients, he found that after a meal the pulse was katacrotic, although before the meal it had been anacrotic. According to Fleming (33), after a meal the pulse waves are higher and he concluded from that that the intracranial tension was lower, but, as in all his remarks he completely ignores the possibility of an "active" increase of intracranial pressure, one is not entitled to come to this conclusion without more evidence.

Effects of meals.

The writer has not been able to get tracings bearing on this question.

II. RESUMÉ OF WORK AND LITERATURE ON THE INTRACRANIAL CIRCULATION.

It will greatly conduce to a proper comprehension of the theories and arguments which have been advanced in connection with the intracranial circulation in the closed skull, to make a historic sketch of the chief views which have been held in connection with the subject, and the reasons for which these have been advanced. The present does not pretend to be altogether a full record of these but will touch on the chief works, and a few of them will be referred to at some length as they bear a very important and interesting relation to the questions which will come up for discussion in the next part of the thesis.

Early writings on the brain movements in the unclosed skull.

Pliny seems to have been the first, so far as has been ascertained, who spoke of the movements of the brain, for although Hippocrates refers to the fontanelle and its closure he makes no direct reference to its movements. After Pliny, Galen also refers to the movements of the brain in the enclosed skull and speaks of its causation. He noticed that movements of the brain coincided with the respiratory movements and suggested that during inspiration, air was sucked into the head and especially the lateral ventricles, through the ethmoid sinuses, whilst during expiration, the air was expelled through the sutures, ethmoid sinuses, etc. Galen's views are repeated by Oribasius, but from a passing reference it would seem that the arterial pulsation of the brain had also been noticed. Later, movements of the brain were described by Fallopius, Vesalius and Gaspar Bauhin, the first and last of whom ascribed it to pulsation of the vessels of the dura. Still later, Willis and Mayow describing the movements in the unclosed skull thought they were due to the movements of the dura. They described motor fibres in the dura and thought that the contraction of these fibres was the cause of the brain pulsations. This theory was further elaborated by Baglivi, who with Pacchoini described two layers of muscular fibre in the dura, and they asserted that the alternate contraction of these gave rise to the alternating movements seen on opening the skull. Vieussens, Bourdon and others supported the idea that the movements were due to the arteries of the dura, Frederic Hoffmann, Santorini and others supported the theory of the independent movement of the dura; a theory whose first advocate -

according to Lorry (4) who gives an interesting historical sketch of the controversy up to his own time, and from whom most of the other accounts are borrowed - had been Rufus of Ephesus. Boerhaave threw his strong influence into the scale in favour of the movement being due to the pulsation of the arteries of the dura; because he said after the dura was cut, no more movement was seen, although before section of the dura, it had been quite evident.

Riolan described movements of the brain in men who had lost part of the calvarium through syphilitic disease, and also in sheep after part of the skull had been removed.

Such was the state of confusion in which this subject was placed in the middle of last century, but then, within a period of 10 years a series of most important contributions completely revolutionised the state of the knowledge on the question.

Writings of Schlichting

The first of these was by Schlichting (1) who in 1750 shewed that the movements of the brain coincided with the respiratory movements, that with expiration the brain was expanded and with inspiration it contracted, i.e., the very reverse of what Galen had described. He did not venture, however, to give any reasons for these respiratory movements of the brain, His work, nevertheless, led to much more investigation and was undoubtedly the starting point of all the observations and discussions which have been going on almost unceasingly from then until the present day.

Lamure (2) - in 1753 - experimenting on dogs found that the respiratory movements took place as Schlichting had described. He found that everything in the neck - arteries, etc., - except the jugular and vertebral veins could be ligatured or cut without affecting the movements, and therefore he came to the conclusion that with expiration the blood was forced back through the veins of the neck into the brain by means of the compression of the chest walls. He proved also, that the veins of the brain were expanded during expiration. Lamure

Haller (3) in an important contribution in 1756 shewed that in dogs, cats, etc., whose brains have been exposed there is a double movement, (a) respiratory movement as described by Schlichting and (b) a movement synchronous with the pulse. He shewed that the depression of the brain in inspiration was due to the descent of the diaphragm during inspiration allowing an easier passage of blood from the veins into the chest, whilst the bulging during expiration he ascribed to compression of veins in the thorax by the chest walls during that Haller period. He also proved that during inspiration the veins of the abdomen are distended, not collapsed as those above the diaphragm - a fact which was evidently lost sight of till Mosso (37) less than 20 years ago, again drew attention to it and demonstrated its extreme importance in the consideration of the question of alterations in arterial tension with the respiratory movements, etc.

Haller found that the expansive movements of the brain were much greater during crying, and during deep respiratory movements.

In 1760 Lorry (4) presented to the Academie des Sciences in Paris, a most interesting paper, in which he gave a sketch of the history of the question of brain movements up till his own time. He discusses the question of the movements being an independent movement of the dura and concludes that that is impossible. Lorry

He experimented on dogs, sheep, cats, etc., and found that although in some there was no movement, in others there were arterial and also respiratory pulsations, the latter of which he ascribed to blood being forced back along the veins into the skull during expiration.

In discussing the circulation in the closed skull, he holds that as a rule no movement of the brain can take place, but adds, "il est certainement des cas, on l'effort du sang vers la tête étant considerablement augmenté, je suis persuadé qu'il peut se produire dans la tête un mouvement, puisque le cerveau est capable de compression. Par example, le sang étant chaffé avec plus de vivacité et de force, les mouvements des artères peut, en ebranlant toute la masse de cerveau, produire un pareil mouvement dans les sinus et occasionner au sang un retour prompt et impetueux dans lès veines, mais inégal." and he adds, that it is for this reason that there are on the jugulars as they leave the brain dilatations, viz: that they may hold this excess of blood. This is the first mention the writer has found of the proposition that blood may be pressed by the arterial pulsation from the venous sinuses out of the skull - a proposition which will receive a considerable amount of attention later on in the thesis. (Page 107).

Soon after this Cotugno (5) drew attention to the fact that in the cadaver the space between the membranes on the one hand, and the brain and spinal cord on the other, was occupied by a liquid present both throughout the spinal cavity and in the cranium. In the living animal this liquid must also be present or the space must be occupied by a watery vapour Cotugno which condenses after death, and he inclines to the opinion that it is a liquid which is present 'intra vitam' also. This observation though of such value, was practically lost sight of until Majendie again described it more than half a century later and drew attention to its great importance to the central nervous system.

The next contribution of importance was that of Monro (Secundus) (6) who taught that as the skull was a closed box, the quantity of blood inside it could not vary unless under certain pathological conditions where its place was taken by effusion. (It must be remembered that at this time Cotugno's discovery of the presence of the cerebro-spinal fluid had been lost sight of) This teaching seems to have been accepted by the majority of the profession in Britain at least, and many years later one of his pupils, Dr George Kellie (8) of Leith, read before the Medico-Chirurgical Society of Edinburgh a paper "On Death from cold and on Congestion of the Brain" in which he supports the arguments laid down by Monro. He shewed by many experiments on animals, that after haemorrhage by arteriotomy, or venaesection the blood vessels of the brain are not emptied although the animals be held up by the ears, whereas if before the bleeding the cranium had been opened

Monro (Secundus)

Kellie

and the brain exposed to the atmospheric pressure and then the animal held up by the ears, the brain was found practically completely depleted of blood.

Carson, (9) about the same time also supported the same view. He likewise shewed the aspiratory action of respiration on the veins of the head even when the head was lowered; and in discussing the circulation in the closed skull held that room must be made for the blood entering the skull at each arterial pulsation and that this room was provided for by blood being forced out of the veins - shewing in fact that as well as the vis a tergo action of the arteries there was also a lateral pressure on the veins. Carson

Abercrombie (10) in the same journal, whilst discussing apoplexy, says that some cases of it are caused by the arterial pressure becoming so high that they press on the veins leaving the skull and so prevent blood coming out. Abercrombie

During the time that these important contributions to the circulation in the closed skull were emanating from the Edinburgh School, various contributions to the study of the movements of the brain in the unclosed skull were being made abroad.

Richerand (11) thought that the arterial pulsation of the brain was not a true expansion, but Richerand merely a heaving of the brain as a whole, from the expansion of the arteries at the base, and this view was supported by Bichat and Burdach (12) as well as others - a theory which they founded on experiments which need not be further referred to in this resumé as they are quite fallacious.

Of much greater importance was the work of Ravina (7). He trephined animals, fixed on the trephine opening by means of a fixing mixture, a hollow wooden cylinder and over this a watch glass - all air tight, he says. The movements of the brain were still visible. As there was a considerable quantity of air between the watch glass and the brain the results are fallacious, but the esperiment is interesting as being practically the same as that afterwards performed by Donders (20). Ravina

Ravina also shewed the movements of the brain by inserting a glass tube into the trephine hole and filling the tube with water, when one readily saw variations on the level of the water in the tube corresponding to the movements of the brain beneath.

In 1825 Majendie (14) described fully the presence of the cerebro-spinal fluid, in the living animal, which although already discovered by Cotugno (5) and hinted at by Haller (3), seems to have been forgotten. He shewed its presence in the subarachnoid Majendie space both in the cranium and in the spinal cavity, as well as in the lateral ventricles and called attention to its probable functions.

Amongst these he suggested that it flowed between the cranial and spinal cavities in the varying conditions of pressure necessarily present during the respiratory movements. During inspiration he said the veins inside the spinal cavity were emptied and as a consequence fluid was drawn into the spinal cavity, whilst during expiration as these veins became engorged whilst the sinuses of brain because of their rigid walls could not, fluid was forced out of the spinal cavity into the cranium and thus was the cause of the rise of the brain during the expiratory period.

This work had an extremely powerful influence on the discussion of this question, and his theory was widely accepted - amongst others by Ecker (15) who thought that the expansion of the brain during expiration was due to fluid being forced from the spinal cavity, up into the lateral ventricles of the brain. Ecker

A little later as we shall see this theory was somewhat modified but nevertheless the cerebrospinal fluid was assigned an influence in the circulation of the central nervous system which could not be over-rated and from this time onward the discussion of the question became even more confusing and difficult than it was before.

Soon afterwards Bourgougnon (13) approaching the subject from a different point of view, made some experiments on the skulls of animals. He trephined the skull, then put over the trephine hole a glass tube which ended below in a conical part, and was fixed in an air-tight manner to the skull. Towards the upper third of the glass tube there was a stop-cock. Having filled the glass tube with water he saw very distinctly the movements of the fluid with respiration and also the arterial pulsation. He then turned the stop-cock and there were no longer any movements seen, and so Bourgounon concluded that in the closed skull there are no movements of the brain although in the open skull there are. This observation of Bourgougnon was a very important one, and although Salathé (31) and others suggested that it was fallacious, it seems to have proved in one way what long afterwards was shewn by Donders (20) and others by quite different methods. Besides quite recently Wertheimer (65) practically repeating the experiment got the same result.

Bourgougnon

Bourgougnon's conclusions were accepted, amongst others by Longet (22) who after a careful and interesting review of the work done up till that time says, "Il resulte que, chez l'adulte, il n'existe pas de mouvement du cerveau." Longet apparently thought that the brain was somewhat compressed, when rise of arterial or venous pressure occurred. Longet

Bergmann (16) in 1844, representing the skull by a box in which was an ingoing tube dividing into branches which again united to form an outgoing tube, the whole surrounded by fluid, and the openings for the tubes being airtight, came to the conclusion that the quantity of blood inside the skull does not vary. Bergmann

Burrows, (17) discussing the disorders of the cerebral circulation refers to the works of Monro (6) Kellie, (8) and Abercrombie (10) and repeated some of Kellie's experiments, but came to very different conclusions. He agreed with Kellie that one cannot empty the vessels of the brain altogether by bleeding the animal slowly to death, but he holds that, nevertheless, the quantity of blood inside the cranium may vary, as shewn by the fact that the brain of an animal bled to death looks pale when examined, whilst the vessels of that killed by strangulation are engorged. This alteration in the quantity of blood in the brain he believed to be Burrows permitted by (1) the elasticity of the brain, and (2) the flow of the cerebro-spinal fluid.

What Burrows seems really to have proved is that the quantity of blood in the veins and especially in the large veins on the surface of the brain, may vary; but of course this is no proof that the quantity of blood inside the cranium as a whole alters.

In the Nederland Lancet of 1850 two papers of considerable interest appeared on the subject of the intracranial circulation.

The first by Berlin (19) was chiefly theoretical. Berlin
He held that as the pressure in the larger arteries inside the cranium increases, the pressure of the cerebro-spinal fluid increases and therefore more is absorbed, so that with increased arterial pressure there is less fluid, and vice versa. He also asserted that the pressure of the fluid is equal to the blood pressure in the arteries minus the "tone" and "elasticity" of the vessel walls. As the "tone" usually remains the same, he held that with decreased arterial pressure the vessels are smaller, there is less blood inside the cranium whilst the quantity of fluid is greater. The evidence brought in favour of this is, however, quite insufficient and indeed in some cases - as in

animals killed by strangulation where there was both more blood in the veins and apparently more fluid on the surface of the brain - is quite contradictory. The chief error in Berlin's argument is the neglect of the venous side of the circulation, which as we shall subsequently see, is of the foremost importance in determining the intracranial pressure. One will see, however, how very similar some parts of his arguments are to those advanced by Geigel (47) only a few years ago.

Donders' (20) work was of a much more practical character. He set himself specially to settle the question whether there are movements of the brain in the closed skull. Trephining the skull in rabbits, he fixed a glass plate on the opening in the skull, the space between this plate and surface of membranes being filled by fluid, and then observed the membranes. Although there were distinct movements of the membranes both respiratory and arterial when the opening was unclosed, these ceased when the glass plate was properly fixed on. Pulsations in the arteries of the membranes could still be seen. This is practically a repitition of one of Ravina's (7) experiments, but the result got was quite antagonistic because apparently in Ravina's experiment a considerable quantity of air was

Donders

present beneath the glass plate, which falsified his observation. Donders also shewed the very important influence of respiration on the cerebral veins.

Ackermann (23), after trephining and putting on a window over the trephine opening observed dilation in the vessels of the membranes when respiration was interfered with and so came to the conclusion that the quantity of blood inside the skull could vary, a conclusion by no means justified by his experiment because although in such a case no doubt the veins are engorged, it does not necessarily follow that there is more blood inside the cranium.

Ackermann

Kussmaul and Trenner (21) in investigating the causation of fits, repeated Donders' experiments, and found with him that there was no movement of the brain with respiration. On the other hand when respiration was interfered with, the membranes became darker, whilst with pressure on the carotids they became paler, and so they concluded that the idea that the quantity of blood inside the skull does not vary, is quite wrong. Here again, however, as in the cases of Burrows (17) one must remember that although the quantity of blood in the veins of the surface may vary during such experiments which interfere with the return flow of venous blood, etc., it does not necessarily follow

Kussmaul and Tenner

that the total quantity of blood inside the cranium varies.

A modification of the views of Majendie was made by Richet (24) about 1860. Exposing the suboccipital (occipito-atlantoid) ligament in animals he noted pulsation of it with respiration (an observation first made by Ecker) and asserted that this was a proof of the movement of the cerebro-spinal fluid, although the theory of the manner in which this movement is brought about, propounded by him, differs from that of Majendie, Ecker and others. During inspiration the sinuses of the cranium being emptied the fluid passes from the spinal cavity up into the cranium which is entirely a closed box, although the spinal cavity is not, whilst during expiration the intracranial sinuses being distended, fluid is driven into the spinal cavity where room is found for it by the occipito-atlantoid ligament, and to a less extent the other spinal ligaments, being distended, and by the adipose tissue inside the spinal canal being pressed through the intervertebral foramina. This theory in its main particulars, viz: that the passage of fluid during expiration is from the cranium into the spinal cavity where accommodation is made for it in various ways, and that this passage of fluid occurs both

Richet

with arterial pulsation and during the expiratory movement, has since then been the one generally accepted, and is so probably at the present day.

Thus, the younger Richet (36) writing in 1881 says, "Il s'ensuit qu'à chaque pulsation cardiaque le cerveau se gonfle, se remplit de sang et augmente de volume, mais le liquide cephalo-rachidien, comprimé ainsi entre les hemisphères et le crâne, reflue vers la moelle epinière, de sorte que le cerveau n'est pas comprimé."

Another most important step in the investigation of the intracranial circulation was made by Leyden (25) in 1866, when he took for the first time tracings of the membranes of the brain. After trephining, he used an instrument somewhat like a sphygmograph, which he did not describe as he recognised that the tracings were not very satisfactory. One can see, however, on the tracings respiratory undulations. He shewed that the movements could also be seen readily by connecting a canula fixed in the trephine hole with a barometer. Experimenting on dogs, he practically repeated the observations of Bourgougnon's shewing that when there is an opening to the atmosphere in a cannula fixed in the trephine hole, the movements of the brain are seen, whilst as soon as the atmospheric

Leyden

pressure is cut off the movement is no longer visible.

From this he concluded that, the quantity of fluid inside the skull does not vary with the pulse or with respiration, although the pressure may.

Leyden also made very important observations on the symptoms produced by the gradual increase of intracranial pressure.

Quincke (27), in 1872, published the results of a series of observations on the movements of the cerebro-spinal fluid. Quincke

In one series he made injections of cinnabar in suspension into the subarachnoid space of the cord, without opening into the spinal column. He injected through the spinal ligaments. The animals (dogs) which lived were killed in from one week up to several months after the injection. Others died in 12 to 72 hours after the injection. The coloured granules were found to have passed usually right up to the base of the brain, and practically always, pretty well along the spinal nerves.

Of the cranial nerves the optic usually shewed the granules along its sheath in largest numbers. The pigment was also usually found along the sheath of the carotid and also in the cervical and sometimes in the submaxillary glands.

In another series of cases a small hole was bored in the skull, a coloured injection made as in the spine, and then the opening in the skull closed by a wooden peg. In these cases the pigment was found at the base of the brain, along the sheath of the carotid and in the lymphatic vessels.

These results, Quincke thinks, prove that there are movements in the cerebro-spinal fluid with respiration, etc., as described by Ecker.

The granules flowed more easily from cord to brain than from brain to spinal cord and so Quincke thinks the former must be the stronger stream. His experiments will be referred to in greater detail later on. (see page 96).

Langlet (28) tried to use the sphygmograph to take tracings of the fontanelle movements in children, but no very satisfactory results were got from the fact, that the children were wakened by the noise of his instrument. He concluded, however, from such as he was able to take that during quiet respiration there was no effect of the respiratory movements on the brain. Langlet

It was Salathé, (31), however, who, in a clear and extremely interesting paper, first shewed by the graphic method, how much could be learned from the observation of the brain movements in the Salathé fontanelle of the child, in gaps in the skull in adults, who through injury or disease had lost part of their calvarium, as well as in animals where part of the skull has been removed. He used Marey's tambours and a revolving cylinder, and he gives a considerable number of the tracings so taken. He comes to the conclusion that during sleep, and in the quiet state, respiration has no effect on brain movements, whilst during agitation, crying, etc., the movements of the fontanelle are very marked; and that during alterations in attitude the tracing also varies.

In his experiments on animals, he shews that when artificial respiration is carried on by inflating the lungs through a catheter,the movements of the brain are the very reverse of what they are during natural respiration, because in the latter, during inspiration there is a better venous return to the chest, from there being a negative pressure in the chest, whilst in the former the venous return is impeded by the forcible distension of the lungs produced by inflation.

He shewed also that there were movements of the spinal cord, similar to those in the brain, but he thought the latter were not due to the influence of the respiratory movements on the veins in the spinal column itself, but were caused by movements in the cerebro-spinal fluid resulting from the movements of the brain.

Coming to the consideration of the question as to whether movements occur in the brain in the closed skull, he supports Richet (24) and his school in thinking that undoubtedly there are. The experiments of Donders (20) and others, who put windows in the skull, he does not think conclusive, as probably the movements would occur chiefly at the base of the brain where the vessels are largest. He tried to prove his contention by making a mechanism comparable to that of the cranial and spinal cavities, but as in this he represents the skull by a rigid walled globe, whilst the spinal cavity is represented by an elongated tube with flexible walls, he practically takes for granted what he sets himself to prove, and the conclusions come to from this part of his thesis are of little or no value.

After Salathé, other pupils of Marey contributed papers on the tracings of the brain, which added to our knowledge of the circulation in the unclosed skull. Amongst these were Brissaud and François-Franck (32), who recognised that as the general level of the brain tracing rose, the arterial pulsations became smaller.

Brissaud & François-Franck.

Soon afterwards, Fleming (33) of Glasgow, contributed a paper, shewing some results got by the graphic method in two patients with gaps in the skull. He shewed that compression of the femoral arteries, coughing, exertion of all kinds caused a rise of tension, as did change of posture of the head, compression of jugular veins, raising the arms, etc. During sleep, he still saw the respiratory curve present whilst the pulse waves were smaller. He sums up thus "The important factors then, in producing cerebral motion, are, the alternate aspiration and expulsion of blood by the inspiratory and expiratory motions of the thorax; the greater or less force of the ventricular contraction; the increased or diminished quantity of blood available to be sent to the brain, and the action of gravity upon the cerebro-spinal fluid." Fleming

In 1881 appeared Mosso's (37) work, "Ueber den Kreislauf des Blutes im Menschlichen Gehirn" some parts of which had, however, appeared some years before. This is undoubtedly the work of greatest interest and importance on the subject within recent years. Mosso investigated the movements of the brain in several patients with a gap in the skull and first drew attention to the fact that on tracings from the brain one could, practically Mosso always, see three prominences - hence he called the pulse "tricuspidal." As a rule the pulse was anacrotic - but occasionally it was katacrotic. He shewed that respiration might affect the form of the pulse, thus whilst during expiration the pulse was anacrotic, during inspiration it might become katacrotic. Above all he drew special attention to a comparison of this pulse tracing of the brain as taken by means of air conduction and Marey's tambours, with the tracing of the arm as a whole taken by means of the plethysmograph - shewing that in both cases the pulse was usually anacrotic; that the respiratory movements might affect the form of the forearm pulse in the same way as they affect the brain pulse, i.e. during expiration it may be anacrotic, whilst during inspiration it may become katacrotic. He directs attention at the same time, to the fact that all parts above the diaphragm are affected as regards the blood in the veins in the same way, viz: during inspiration there is an aspiration of the veins of the neck with consequently increased venous flow in head and arms, whilst below the level of the diaphragm, as, during inspiration, the veins of the abdomen are pressed on by the increase of the abdominal pressure during that act, the venous return especially from the legs is retarded, so that there is a tendency for the effects of the lower part of the body to counterbalance that in the upper, and so to produce a regular supply of blood to the heart.

He made elaborate investigations on the effect of mental efforts on the brain and found that every mental effort and practically every stimulation of the senses produced increased intracranial tension as indicated by a rise in the level of the tracing. This rise of tension in the brain was nearly always accompanied by diminution in the volume of the arm, as taken by the plethysmograph. In some cases, however, there was rise of intracranial pressure without apparent alteration in the volume of the limb. During mental effort also the pulse waves were more ample, as well as the general pressure being higher.

He shewed also that the tracings shewed waves which were independent of the respiratory waves and of the arterial waves, and were evidently due to rhythmic action of the vessel walls, similar to what is seen in the vessels of the rabbit's ear.

During sleep the brain pressure was shewn to be low and the individual pulse waves small.

He also held that in the closed skull there was pulsation in the veins, as shewn by his experiment of putting a canula in the longitudinal sinus and filling up rest of trephine hole by a rigid plate.

Mosso came to the conclusion that during ordinary respiration there was practically no movement of the cerebro-spinal fluid, although his experiments were fallacious inasmuch as they permitted atmospheric pressure to come into play.

François-Frank and Pitres.

In the Dictionnaire Encyclopédique des Sciences Médicales (1887) François-Franck and Pitres (42) contribute an article of great interest and value to the subject, under the heading "Encéphale - circulation." Reviewing the whole subject they shew the effect of the heart's action and of respiration on the intracranial circulation in the unclosed and then in the closed skull. They believe that the heart's action affects the venous circulation in the brain in three ways - 1st, by the ordinary _vis a tergo_ action of the blood forced through the arteries and capillaries; 2nd, by the lateral pressure exerted on the veins by the dilating arteries; and 3rd, by the aspiratory action on the sinuses of the right auricle when it dilates. They discuss the question of the movement of the cerebro-spinal fluid and they refer to some experiments of theirs directed towards the determination of this question. Inserting a fine haemodromometer through the occipito-atlantal membrane, apparently into the subsrachnoid space, they watched for movements. With ordinary respiration they saw none, with arterial pulsation the instrument moved in one direction, whilst between the pulsations it moved in the other. They therefore came to the conclusion that with arterial pulsation there was a flow of fluid from cranium into the spinal cavity, but with respiration there was none. They think, however, that with forced respiration there is a flow from the one cavity to the other, but they could not prove it experimentally as they were unable to get the animals to take forced respirations when they desired them. The chief reason for thinking that such a flow during forced respiration takes place, is the fact that during inspiration the flow from the cord will not be so great as from the brain, consequently fluid should flow from the spinal column into the cranium.

The negative result as regards the movement of fluid with the respiratory movements got from the above experiment is of great interest though too much value must not be placed on it; but one cannot but be sceptical as to the conclusions derived by the authors from the movements of the haemodromometer with the arterial pulsations. It would be quite impossible to be sure that the instrument was really free in such a small space as the subarachnoid space of a dog, and the movements could quite easily be imparted to the instrument, were the point resting on the spinal cord or against an artery in the membranes without any movement whatever of the cerebro-spinal fluid taking place.

They also shewed that when the skull is unopened the difference of pressure inside the carotid artery, when the animal is raised from the horizontal to perpendiculer position, is not nearly so great as it is when the skull is opened - or as it is in the arteries of the limbs. This demonstrates very clearly the difference even in the arterial side of the intracranial circulation, between the circulation in the closed from that in the unclosed skull.

About this time Gärtner and Wagner (43) approached the subject from quite a different standpoint. Gärtner & Wagner.

They experimented on dogs and estimated as far as possible the amount of blood flowing through the brain; using for the purpose the vein which conveys most blood from the head in the dog, and estimating the quantity by means of the kymograph. They found that with pressure on the aorta and consequent rise of intra-arterial pressure whilst the venous pressure is not affected the blood flow is increased. Amyl nitrite whilst causing decreased pressure increases the flow of blood too, so that the vessels of the brain are evidently dilated and a similar condition seems to be present in the late stages of chloroform anaesthesia. These results of Gäertner and Wagner are of much interest, though of course the method used cannot give exact results, and of course only very indirect and inconclusive evidence of the variations in the calibre of the blood vessels inside the skull can be got. An important point shewn by them is that sensory stimulation whilst causing contraction of the vessels throughout the body generally, causes an increased flow of blood through the brain - hence they come to the conclusion that in shock, probably there is not anaemia of the brain, but rather that the pressure of blood inside the cranium is very high. We shall see the importance of this point at a later part of the thesis. The fact that sensory stimulation did not cause contraction, but dilation of the vessels of the brain had already been shewn by Knoll (40), who made observations on the pressure

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of the central nervous system by a cannula inserted through the occipital membrane.

Roy and Sherrington (49), in 1890, made a valuable contribution to the work on the blood supply of the brain by measuring directly the changes which occur in the thickness of the brain itself after the subarachnoid space had been opened - and they concluded that the blood supply of the brain varies directly with the blood pressure in the systemic arteries. They sought for, but could find no evidence of any vaso-motor nerves to the brain, and nearly every rise of blood supply to the brain observed in the experiments was evidently due to increased pressure in the systemic arteries. An exception to this was the dilatation seen when free acids were injected into a vein, and they came to the conclusion that the acid acts directly on the walls of the blood vessels causing an active dilatation of the vessels. With anaemia of the brain they found that there was excitation of the vaso-motor centre, with contriction of the arteries of the body, rise of blood pressure and consequent increase of the blood supply to the brain.

Roy and Sherrington

In Virchow's Archiv for 1890, appeared a series of articles on the "Circulation in the brain and its variations" by Geigel (47), who starts

Geigel

with asserting that the doctrine laid down by Althann (26), that overfilling of the arteries causes a slowing in the blood-stream by raising the intracerebral pressure, is an incontrovertible fact. He emphasises the fact that the question of importance is not the quantity of blood in the arteries or veins of the brain, but the rate of flow through the capillaries and consequent freedom of exchange of chemical products, and so he proposes to use, not the terms anaemia and hyperaemia, but the terms Eudiaemorrhysis - proper flow of blood through the capillaries; Adiaemorrhysis - lessened flow; and Hyperdiaemorrhysis - increased flow. Accepting the cranium as practically a closed box, he says that the intracranial pressure is equal to the intra-arterial pressure minus the resistance which the tension of the vessel wall offers and from that (using algebraic methods) he argues that with lessened tension of vessel wall and consequent dilatation of the artery the rate of flow through the capillaries is decreased, and conversely he holds that spastic contraction of the arteries of the brain causes hyperdiaemorrhysis. He asserts also that the rate of flow in the brain capillaries is much more dependent on the tension of the vessels than on the height of the arterial pressure, and that the question of the influence of increased arterial pressure - from increased heart's action - depends on the tension of the vessel walls. The tension of the artery walls not only influences the rate of flow in the capillaries but also, he holds, the width of the capillaries, for with increased tension of the walls the intracranial pressure is less and the capillaries are less pressed on whilst with diminished tension, the intracranial pressure is increased and the capillaries are pressed on, therefore high tension of artery walls produces hyperdiaemorrhysis, low tension produces adiaemorrhysis.

This paper of Geigel's produced a reply by Lewy (48) of Berlin, who after referring to the experiments of Donders as shewing that variations in the quantity of blood inside the cranium can exist, and asserting that these variations are rendered possible by the flow of cerebro-spinal fluid from the cranium into the spinal cavity, proceeds to examine Geigel's arguments. He says that in referring to the 'tension' of the vessel wall, Geigel has omitted the action of the muscular coat of the arteries, and he asserts that the intracranial pressure depends rather on the difference between the arterial and the venous pressures than

Lewy

on the arterial pressure as Geigel holds. If Geigel's theory were correct, on opening the skull the regulation of the blood supply would be completely altered, for then as a rule it corresponds to the blood supply of the rest of the body, i.e. with dilated arteries there is a greater blood flow, and vice versa, and it is impossible to imagine that such a change from one form of regulation of blood supply to another, the exact counterpart of it, could be accomplished without serious phenomena supervening - but no such phenomena are seen -

Lewy concludes that with the dilatation of the arteries of the brain, as much lymph as possible passes out of the cranium into the spinal cavity, that after this further pulsatile widening of the arteries, is accompanied by pulsatile narrowing of the capillaries and veins, but that only when the area of the capillaries and veins is decreased by compression to less than that of the arteries, does the blood flow through the capillaries become lessened. Therefore narrowing of an artery in the brain causes arterial anaemia, widening of an artery causes arterial hyperaemia, and only very great widening of an artery as already explained, causes a lessened flow of blood through the capillaries - and so except in extreme dilatation of arteries the regulation of the blood flow through the brain is the same as that in any other organ of the body.

In his work on "The Intracranial Circulation" published in 1890, Dr Cappie (46) of this City argues at considerable length in favour of the views held long ago by Kellie (8), and Carson (9). Cappie

He thinks that the view that cerebro-spinal fluid may pass from the cranium into the spinal cavity, and vice versa, is negatived by the facts, that if that were so, (1) the fluid could not give proper and constant support to the brain which is admitted to be one of its chief functions; (2) There would be a great stress on the nerves at the base of the brain which would necessitate their being extensible, but as that is not the case with many of them at least, would result in their injury; (3) Further he argues that if the dura is fibrous it cannot distend and accommodate more fluid, and if it is so distensile as to accommodate more fluid it could not again drive the fluid back into the brain. It must be said, however, that these arguments are very far from convincing, and the work, which had partly appeared many years previously in the Edinburgh Medical Journal, does not treat of the later investigations into the subject.

In 1892 appeared a work by Grashey (50), on the blood circulation in the brain. From observations on a mechanism which he made to represent the circulation inside the brain, he came to the conclusion that with rise of pressure in the aorta there was increased flow of blood through the brain capillaries until a certain point was reached, when the veins began to vibrate and then to be compressed with consequent rise of intracranial pressure but decreased flow through the capillaries. The part of the veins which vibrated and became compressed was that where the veins emptied into the sinuses - the walls of the latter being firm could not be compressed. As a result of this compression there was congestion of the capillaries and the quantity of cerebro-spinal fluid was also probably increased. All this tended to cause still further rise of intracranial pressure and further compression of the veins, and thus a vicious circle was set up. Grashey

About the same time Tietze (51) made a short contribution to the graphic representations of the brain movements. He took tracings from a boy with a hole in the left frontal region of the skull, and used three methods. (1) By a lever resting directly on the brain. (2) By air conduction, and Tietze

(3) By water conduction. In the two former the pulse was anacrotic, in the later it was katacrotic.

He found also that the pulse wave of the brain was $\frac{2}{100}$ of a second later than that of the carotid. This difference corresponded he says to the distance to be travelled by the wave in this patient, and shewed in his opinion conclusively that that wave was produced in the brain substance, and was not transmitted from the vessels at the base of the brain.

A paper of interest by Dean (56), "On cerebro-spinal pressure" appeared in the Journal of Pathology and Baeteriology - Vol: I, 1893. He shewed the distinction between general and local compression, and considering the former first, he estimated the cerebro-spinal pressure by passing a cannula up the sheath of one of the spinal lumbar nerves. The normal pressure in the dog he found to be 70 to 150 m.m. of water. Any diminution of space in the cranial cavity was found to cause at once a rise, and only a gradual rise of pressure. No sudden rise on further diminishing the space was found although described by Bergmann and others. This shews that the theory that fluid passes into the theca and so prevents an immediate rise of pressure, whilst after all available space from such distension

Dean

of thecal and perineural space has been made use of, there is a sudden rise of pressure is probably incorrect. He admits, however, the possibility of distension of the theca vertebralis on anatomical grounds.

Discussing local compression he refers to the circulatory mechanism of that region of the brain affected by the compressing agent. He inserted glass dics beneath the dura and found that as a result there was marked anaemia followed by much oedema. He therefore cannot understand how Adamkiewicz, who used pieces of laminaria in the same way, got from the pressure of these not anaemia but hyperaemia of the small vessels.

Experimenting on the action of various conditions of the cerebro-spinal pressure and recording at the same time the arterial pressure, he found that these did not always rise and fall together, and therefore he came to the conclusion that these experiments shewed that there were vaso-motor nerves to the brain. It must be remembered, however, that in these experiments of Dean, no notice was taken of the venous pressure.

What is probably one of the most important of the contributions to the question of the cerebral circulation has been recently published by Bayliss and Leonard Hill (68). They shew the necessity in discussing the question of the intracranial pressure and the cerebral circulation, of taking into consideration three factors; (1) The general arterial pressure; (2) The general venous pressure; and (3) The intracranial pressure. This intracranial pressure was found by them to correspond always with the pressure inside the intracranial venous sinuses and they assert that the cerebro-spinal fluid is not secreted at a higher pressure than that of the intracranial venous pressure. Bayliss and Hill.

Everything which increases the general venous pressure, increases the intracranial pressure; and if the general venous pressure be constant, the intracranial pressure rises or falls with the general arterial pressure. When the general arterial and general venous pressures are not constant, however, the intracranial pressure follows the venous pressure more quickly than the arterial.

When pressure inside the skull is raised, some cerebro-spinal fluid flows out into the spinal column, but then the brain sinks into the opening of the foramen magnum and no further rise of pressure from the cranium is transmitted into the spinal column and therefore all experiments based on conclusions got by estimating the <u>spinal</u> subdural pressure as an index of the intracranial subdural pressure (Falkenheim and Naunyn (45) - Dean etc.) are valueless except for slight pressure before the brain has sunk and plugged up the foramen magnum. It therefore follows that any expansion of the brain which occurs from rise of arterial pressure is very slight, for only a slight amount of fluid can be displaced into the spinal column.

As soon as this point is reached when no more fluid is displaced into the spinal cavity, any further expansion of arteries or narrowing of the space of the cavity can only take place by compression of the capillaries and veins, and then the intracranial pressure rises rapidly.

The intracranial pressure is the tension which remains after the force of the heart has been expended in driving the blood through the cerebral arterioles. It is therefore the same as the pressure in the venous sinuses and so does <u>not</u> depend on the tension of the cerebral arteries.

On introducing foreign bodies inside the skull the intracranial pressure rises from obliteration of capillaries and veins to the arteriole pressure, and as arterioles are compressed it rises to the arterial tension.

With increased venous pressure there would be increased secretion of cerebro-spinal fluid - if pressure were now decreased, the fluid being at a higher pressure would pass into the veins through the Pacchionian bodies, etc. Any obstruction to the cerebral veins would cause an increased secretion of cerebro-spinal fluid.

They made many experiments, and all these shewed that the intracranial pressure followed passively those alterations in the general arterial and general venous pressures, and therefore there was not the slightest evidence suggestive of the presence of vaso-motor nerves to the vessels of the brain. They say "We are in a position to state that the brain has no direct vaso-motor mechanism, but that its blood supply can be controlled indirectly by the vaso-motor centre acting on the splanchnic area." and they sum up their results thus:-

"1. No evidence has been found of the existence of cerebral vaso-motor nerves; either by means of stimulation of the vaso-motor centre or central end of the spinal cord, after division of the cord in the upper dorsal region; or by stimulation of the stellate ganglion, and that is to say the whole sympathetic supply to the carotid and vertebral arteries.

2. Evidence is not forthcoming of the existence of any local vaso-motor mechanism such as that indicated by Roy and Sherrington. The injection of acids and extract of brain have produced in our hands no active dilation of the cerebral vessels.

3. In every experimental condition we find that the cerebral circulation passively follows the changes in the general arterial and venous pressures.

4. The intracranial pressure is in all physiological conditions, the same as the cerebral venous pressure.

5. The volume of the brain is practically invariable.

6. There is no compensatory mechanism by which the intracranial pressure is kept constant. The intracranial pressure, which in all physiological conditions is circulatory in origin, may vary with the circulatory pressure from Zero to 50 - 60 m.m. Hg. The functions of the brain matter continue in this varying condition of pressure.

7. In all physiological conditions a rise of arterial pressure accelerates the flow of blood through the brain, and a fall slackens it.

8. In pathological conditions where there is occlusion or inflammatory dilatation of large capillary areas in the brain, the opposite effects occur. In these conditions a rise of arterial pressure diminishes the cerebral blood flow and a fall accelerates it.

9. Any foreign body in the cranial cavity will obliterate capillaries, raise the intracranial pressure and produce cerebral anaemia.

10. The brain matter does not suffer from pressure alone, but from pressure producing anaemia.

11. The rise of arterial pressure that occurs in pathological conditions of increased intracranial pressure, is not protective but tends to increase the extent of the cerebral anaemia.

12. The right direction of treatment therefore, in such conditions, is to lower the blood pressure."

Many of these points will come up again for discussion in the next part of the thesis.

Binet and Sollier.

Quite recently Binet and Sollier (71) have recorded some observations on the movements of the brain, in a woman with a gap in her calvarium, but these have been referred to in the first part of the paper (page 15) and so need not be mentioned further here.

III. THE INTRACRANIAL CIRCULATION IN THE CLOSED SKULL.

Having considered the peculiarities of the circulation in the unclosed skull, and noted the chief views held on the subject of the intracranial circulation, and the methods of investigation by means of which these views have been arrived at, we are now in a position to take up the consideration of the circulation inside the closed skull.

Contrast between physical conditions in closed skull and those in unclosed skull.

When we reflect for a moment on the condition of affairs in the closed skull, how the brain is surrounded on all sides by the unyielding cranium, it will at once be seen what a difference there is between it and that existing in the unclosed skull. Here obviously the atmospheric pressure cannot come to bear on the cranial contents as it can in the case of the open skull and this is the point of greatest importance, on which most of the differences hinge.

In considering the circulation in the unclosed skull it was seen that the circulation underwent important changes with the arterial pulsation and

and with the respiratory movement. Here, perhaps, it will be well to discuss first the respiratory changes

1. Effects of respiratory movements on the intra-cranial circulation in the closed skull.

Effects of respiration on circulation in closed skull.

We have seen how the respiratory act has a great aspiratory effect on all the veins above the level of the Diaphragm, and how as a result of this action the brain during inspiration becomes depressed from the influence of the atmospheric pressure when the venous pressure is so lowered. In the closed skull we have the same aspiratory action on the veins of the neck and it has been shewn most conclusively by Bayliss and Hill (68) as well as by Mosso (37) that the aspiratory action is also felt in the venous sinuses of the brain so that there is a distinct fall of intra-cranial venous pressure during inspiration. With the inspiratory act then, more venous blood passes out of the cranium: As the cranium is incompressible what takes the place of this blood, which has passed into the thorax?

Decrease of intra-cranial pressure during inspiration.

In discussing this question, it must be kept in mind that there are the three factors to be taken into consideration, in addition to the central nervous tissue, viz:- (1) the arterial blood, (2) the venous blood, and (3) the cerebro-spinal fluid.

Possible results of this.

It has been shown experimentally that the central nervous tissues are practically incompressible and, therefore, when blood flows from the cranial venous sinuses during inspiration, its place must be taken by either arterial blood: cerebro-spinal fluid: or blood from the spinal venous plexuses.

Taking the last of these first, it has been suggested that,

(a) Blood flows from the veins inside the spinal cavity up into the veins of the cranium. The extra-dural veins of the spinal column are very large and communicate freely with those of the brain so that it would be an easy matter for blood so to flow if the conditions were favourable for such a flow. But, the aspiratory action of the respiratory movement is not confined to the veins of the neck and brain, it is also exerted on the veins of the arm and undoubtedly on those of the spinal column, so that at the same moment that the veins of the skull are being emptied, those of the spinal cavity are also being depleted. Hence this flow from spinal to cranial veins cannot take place to any extent worth mentioning.

Is there flow of venous blood from spine to cranium with inspiration?

(b) It is usually accepted as a fact that during inspiration cerebro-spinal fluid takes the place of the blood which flows from cranial veins during that act.

Is there movement of cere-bro-spinal fluid with respir-ation?

The cerebro-spinal fluid of the brain is directly continuous with that of the cord, whilst it can also pass along the nerves as the membranes of the brain and cord pass out and form a sheath over these nerves.

That such movements of the fluid can readily occur has been shown long ago by Quincke (27) and others,who injected coloured fluids or fluids with coloured particles in suspension into the sub-arachnoid space,but that such movements can occur does not mean that they do occur with respiration under physiological conditions. The dura of the spinal cavity hangs freely inside the column and, therefore, it has been said that when,during expiration,there is a damming back of blood inside the cerebral veins, the cerebrospinal fluid is forced out of the cranial cavity into the spinal cavity: In other words that, during expiration the brain bulges from more blood being inside the cranium at that period and that accomodation is made for this bulging by fluid being pressed out into the spinal canal.

Does the brain pul-sate in the closed skull?

But there have always been observers who denied that this occurred and Bourgougnon,as already mentioned, (page 38) as the result of his observations long ago claimed that no such expansion of the brain took place. Salathé (31) thought that his experiment was defective but Wertheimer (65) has quite recently again practically repeated it and when the atmospheric pressure was cut off from the tube of fluid connected with the intracranial cavity no movement of the fluid occurred. Donders (20) again by using a window over the opening in the skull could observe no movement with respiration and the writer, practically repeating Donders' experiment, (of which at the time he was ignorant) came to the same conclusion.

Donders' experiment

EXPERIMENT 1. A large rabbit was etherised, a semi-lunar flap over the vertex of the skull reflected and then a trephine hole ½inch in diameter made; on removal of the disc of bone the membranes were seen to expand and retract with expiration and inspiration respectively, whilst the arterial pulsation was distinctly seen.

A piece of very thin mica was then taken and fixed over the trephine hole with wax, evidently keeping out the atmosphere quite thoroughly and after this was properly fixed no movements with respiration could be seen although the arterial pulsation was still visible.

This was allowed to remain open for a considerable period and no respiratory movement could be made out - it was then removed and again the respiratory pulsations were visible although they were now more faint.

Arguments against its value.

It has been said, however, that although no movement with respiration can be seen with such a window to the skull, it does not follow that no expansion of the brain itself takes place. It is asserted that with expiration the brain itself expands, that the fluid is pressed out of the sub-arachnoid space inside the skull into the spinal cavity and also, perhaps, along the sheaths of the nerves whilst the dura itself does not move - in fact, that which occurs is a diminution in the size of the space between the brain and the membranes from displacement of the fluid in this space. Were such the case it is evident that no observation of the kind described could be accepted as conclusive, for one would require to reflect the membranes to watch the brain itself, whilst if the membranes were cut the fluid at the part operated on would flow out and the conditions would be so altered that no conclusions could be definitely drawn from them.

Again, it is urged as against Bourgougnon's experiment that no movement occurring in the column of fluid after the removal of atmospheric pressure does not disprove such a movement as has been suggested, because the fluid would flow not towards an incompressible surface but towards the spinal cavity and along the sheaths of the nerves, where it is alleged expansion can readily occur.

The writer thought that a method which might throw some light on this question was to inject into the sub-arachnoid space a fluid containing coloured particles in suspension with as little disturbance of the natural conditions as possible, so that if such movement occurred its presence would be shown by some of the particles being carried where the flow had taken place.

i. To discuss then, in the first place, the question of flow of fluid along the nerve sheaths such flow might obviously take place along the cranial nerves, or along the spinal nerves or both.
a. Of the cranial nerves, that whose sheath has the freest communication with the sub-arachnoid space is the optic nerve and it is the one in which Quincke in his experiments found most colour when he injected fluid with coloured particles beneath the arachnoid. As it is also one of the least difficult to get near, it was thought advisable to use it as a test of this alleged flow.

Is there flow of cerebro-spinal fluid with respiration along the nerve sheaths?

EXPERIMENT 2. A large rabbit was etherised a trephine hole made over the anterior part of the brain - The brain was found to be pulsating freely - The olfactory lobe was raised and then close to the origin of the optic nerve from the base of the brain,

Experiments of the writer to test this.

3 minims of normal salt solution with prussian blue particles in fine suspension were injected beneath the arachnoid - The trephine hole was then completely closed up by a metal disc closely fitting and the animal allowed to live for about ten minutes during which it was taking deep inspirations. It was then given chloroform freely till it died.

In order that no movement of the particles might occur through the manipulation of extracting the brain, the body of the animal was frozen and sections were sawn. These were put in spirit for a time, then decalcified in Perenni's fluid, embedded in paraffin and sections cut. It was found that although there were numerous particles near the root of one optic nerve no particles had passed along the nerve.

(It is a matter of great difficulty to know when the point of the needle is in the sub-arachnoid space, but one can easily make sure of injecting particles into it, by inserting the needle a little more deeply into the brain or spinal cord as the case may be, then gradually and slowly withdrawing the needle whilst one gently injects all the time that the needle is being withdrawn. In this way some particles are sure to be left in the sub-arachnoid space.)

This experiment seems to show that no flow of any consequence can take place along the sheath of the optic nerve with respiration else one would have expected to find particles along the nerve - for the respirations after the injection were deep.

Probably no flow along cranial nerves.

β. Spinal nerves

EXPERIMENT 3. Dog - large retriever - Etherised, incision made over spine in the upper dorsal region, muscles reflected, and then trephine hole made with ½inch trephine - a few minims of prussian blue in suspension in normal salt solution were injected into the sub-arachnoid space and then trephine opening firmly plugged with tightly fitting cork. The animal lived for a quarter of an hour fully and was then chloroformed to death, taking very deep respirations just before death. It was then frozen and frozen sections made as in the case of the rabbit in Experiment 2, so as to prevent any movement of particles when the cord was being extracted. Afterwards microscopic sections were cut and here again although there were numerous particles close to the root of the nerve, no particle could be seen along the sheath of the nerve.

Experiments of the writer regarding possible flow along spinal nerves.

EXPERIMENT 4. In another experiment, in a rabbit, where after injection of prussian blue particles in suspension the animal lived fully two days, there was no sign of any particles having passed along the sheaths of the nerves, not even of the nerves close to the point of injection. This experiment is referred to at greater length in its other bearings. (See page 91)

These Experiments seem to prove clearly that under conditions as nearly normal as possible, viz:- closing up the opening so as to keep away the action of the atmospheric pressure, no flow of fluid takes place along the sheaths of the cranial or spinal nerves.

Probably no flow along spinal nerves with respiration.

ii. Much more important is the theory that during expiration, the cerebro-spinal fluid passes out of the cranium and distends the meninges of the spinal cord. It is pointed out that whilst the dura inside the cranium is firmly adherent to the bone and so is not distensile, the theca vertrebralis hangs loose in the spinal column being surrounded by fatty tissue and venous plexuses and so can be readily distended. It is further shewn that when an opening in the vertebral column is made movements of the spinal dura are seen which are exactly synchronous with those which we have seen occur in the

Does the cerebro-spinal fluid flow from cranial cavity to spinal cavity and vice versa with respiration?

Arguments in favour of this.

brain when an opening is made in the skull,and these movements it has been held are transmitted by the cerebro-spinal fluid which then passes downwards into the spinal column.

Again, when the theca vertebralis is exposed and then the intracranial pressure is increased by some means or other, there is seen a distinct bulging of the theca.

And, most important evidence of all, it has been shewn that in some animals when the muscles are reflected and the occipito-atlantal membrane is exposed, this membrane is seen to move in a manner exactly similar to the movements of the theca vertebralis when the vertebral column is opened into.

It is said, in short, that the theca is distensile and that its distension is permitted during the expiratory period partly by the large extra-dural venous sinuses of the spinal column being compressed, partly by the adipose tissue outside the membrane being pressed outside the canal through the foramina between the vertebrae, and partly by the distension of the spinal ligaments, especially the sub-occipital ligament.

Such is the chief evidence which has been brought forward to prove that the backward and forward flow from cranium to spinal cavity and vice-versa occurs during the respiratory periods.

The theory is a very plausible one indeed at first sight and probably under abnormal conditions there is much truth in the description of what takes place, but the writer believes that under ordinary physiological conditions there is much to be said against the theory.

Arguments against this

In the first place, it is obvious that here as in the case of the cranium any movement of the membranes after the vertebral canal has been opened into, is no proof that such a movement occurs when the vertebral canal is intact.

It may be admitted, and indeed has been clearly proved, that alterations in the pressure of the fluid occurs in the spinal canal during the respiratory phases, but this is not necessarily due to the effects of the respiration on the cerebral venous sinuses - in fact, it is certain that inspiration has a similar aspiratory action on the veins in the spinal canal (at all events in a large portion of the spinal canal) to what it has on the cerebral venous sinuses. And as the spinal venous sinuses are extremely large, the influence of inspiration must here also be very great. But because the pressure inside the venous sinuses and so the general cerebro-spinal pressure - for this normally follows the pressure in the venous sinuses - is decreased, if the atmospheric pressure does not come into play there will be no compression of the vessels and consequently no movement of the cord and membranes.

The fact that the occipito-atlantal membrane becomes depressed during inspiration and bulges again during expiration is held to be a proof that the atmospheric pressure does come into play - producing compression of the veins when the venous pressure inside the canal is low - in fact, that the spinal canal is not a closed cavity as the skull may be said to be. That such a movement of the membrane as has been described does occur seems to be certain - and that, when the column is exposed by reflection of the muscles and aponeuroses, with such a movement of the membranes there is also some movement of the cerebro-spinal fluid is probable. But such is not the normal condition of affairs. Covering the occipito-atlantal membrane is a large mass of muscular fibre with tense, firm, non-distensile fibrous aponeuroses and it appears to the writer very questionable indeed whether such a movement can then occur as occurs when the membrane is exposed. The cerebro-spinal pressure is not very high - 7to 10 m.m. of Mercury - consequently, variations of this during the phases of respiration though relatively important,are absolutely not great and it does seem open to doubt whether such small variations could cause distension of a membrane bound down in the manner it is by muscle and firm fibrous tissue.

Similarly, the writer believes that any movement of the fatty tissues surrounding the theca vertebralis through the foramina of the vertebral canal is prevented by the muscles and aponeuroses outside the column.

The cranial and spinal cavities are subject to the same influences

With regard to the extra-dural venous sinuses it may be at once granted that variations in their size dependent on the respiratory movements do occur. But that such movements consist of compression of the spinal venous sinuses during expiration from the pressure excited by the cerebro-spinal fluid which is said to flow from the cranium into the spinal column during expiration, the writer cannot grant. As has been already shewn, with inspiration blood is sucked from the venous sinuses both of the head and of the spinal column, and during expiration there is a damming back of the blood, so that the veins in both cavities are subject to the same influences and there is not the slightest proof that the pressure in the veins inside the cranium is higher than that in the spinal veins which could be the only reason why the spinal and not the cranial veins should be compressed. It is true that the walls of the cranial venous sinuses are firm, non-distensile, and probably are not compressed by rises of pressure inside the cranium, but the veins which open into these sinuses have distensile walls and are in fact under exactly similar conditions to those inside the spinal canal, so that with expiration the veins both of the cranial and of the spinal cavities are distended, whilst during inspiration both these sets of veins are somewhat emptied.

Arguing, therefore, merely from the anatomical conditions present in the cranium and spinal column, the writer came to the conclusion that during ordinary physiological conditions no flow of cerebro-spinal fluid worth mentioning takes place from the one cavity to the other from the respiratory movements. To prove this is, of course, by no means easy, for to make investigations on a canal so completely enclosed as the spinal canal is, without opening it, is uncertain as well as extremely difficult whilst, as already shown, the mere opening it completely destroys the normal state of affairs by allowing the pressure of the atmosphere to come into play.

One at first thought of trying to find whether any movements of the spinal ligaments took place which could be made appreciable by such an apparatus as a plethysmograph, which would enclose the posterior surface of the trunk of an animal; but any movements so shown would not throw any light on the question as the veins in the soft tissues covering the back are also under the influence of the respiratory movements, just as they are in the limbs. It would be impossible, therefore, in any increase in the volume of the back to determine how much was due to such engorgement or depletion of these veins and how much to the movements (if any) of the spinal ligaments.

It is equally impossible to have a spinal column in such a natural condition that it would show how much pressure is required to produce such distension of the spinal ligaments as, it is suggested, occurs, so that other means had to be adopted to investigate the question.

Means of determining the point.

It was determined, therefore, to dissect down to the spinal column, to make a trephine opening in it, then to apply a glass window which would effectually keep out the air and note whether after this was done the movements of the cord naturally seen when the spinal column is opened were still present when the atmospheric pressure was cut off.

EXPERIMENT 5. A large retriever dog, having previously received an injection of 3 grains of morphine, was etherised. An incision was then made in the middle line in the dorsal region for about 3 inches in length, and the muscle carefully reflected from the spines and transverse processes of the vertebrae. (This required a considerable amount of time, as unless in reflecting the muscle one keeps very close to the bone there is apt to be troublesome haemorrhage which would of course render the experiment completely useless.) After what haemorrhage there was, had been thoroughly checked by forceps, and hot water, a $\frac{1}{2}$ inch trephine was applied to the postero-lateral aspect of the vertebral column, and a disc of bone carefully removed so exposing the spinal dura mater. This was bulging somewhat, and the respiratory movements were so very fine that they could scarcely be noticed with the naked eye. As it was recognised that it would be impossible to decide whether such fine movement existed after the glass plate was fixed on, the idea was given up, and it was decided to make an injection of Prussian blue in solution. As soon as the needle pierced the membranes, however, there was a spout of cerebro-spinal fluid, which soon became a flow, and then ceased after a drachm or two of fluid had

Experiments of the writer on this question.

escaped. As soon as this fluid had escaped, the respiratory movements in the cord were very marked, the dura bulging with expiration, and being retracted with inspiration. The flow ceased and then a thread was made on the edges of the trephine opening. The projecting processes were sawn away with a fine saw and a level surface made on the outside of the vertebral canal. Into the trephine opening there was then screwed a brass ring, holding a circular plate of glass, as represented in fig. 37 which fitted exactly the thread made on the edge of the trephine hole. When this plate was lightly placed on the surface the respiratory movements of the cord were still very marked, but when the window was screwed tightly home, <u>no respiratory movement could any longer be seen</u>. Nevertheless the arterial pulsation could still be seen. The brass ring holding the glass was not deep, and did not press on the spinal cord at all. The window was again unscrewed, when once more the respiratory movements became very evident, whilst on replacing the window they again completely ceased.

This experiment, which does not seem, so far as the writer has been able to make out, ever to have been performed before, is of very great importance.

The comparative absence of movement of the spinal cord when the canal was first opened was no doubt due to the high cerebro-spinal pressure present, which was shewn by the fluid spouting out in a distinct stream, when the membranes were pierced by the needle, and by the fact that after a certain amount of fluid had escaped the respiratory movements became quite evident, for it was shewn in the first part of the Thesis, that with high cerebral pressure, respiration had much less effect in causing movements of the brain.

Why the pressure should have been so high, it is difficult to say, although it has been shown that ether in its later stages raises the cerebro-spinal pressure and that morphia has a similar effect.
No doubt in the case of this dog, these drugs had some influence in producing the high pressure present.

No movement of spinal membranes when they are not exposed to atmospheric pressure.

The point of great importance however, is, that here as soon as the atmospheric pressure was cut off the movements of the spinal membranes ceased, just as we have seen such movements of the brain membranes cease when they are cut off from the atmospheric pressure. But in this case the experiment seems to prove more than the corresponding one on the brain, for it is practically certain that if there were any distension of the dura below the level where this experiment was made during expiration, this distension would be shewn by movement of the dura, visible beneath the glass window. And as one of the largest spaces of the spinal dura available, from an anatomical standpoint, for such a distension is the lower end, it may reasonably be presumed that no such distension occurs. It might possibly be urged that although no distension of the dura occurs through the greater part of the canal, yet such distension occurs at the level of the occipito-atlantal ligament, but although the ligament here is larger than anywhere else probably in the spinal column, it is also even more deeply covered by mass of muscle and aponeurosis, than the ligaments lower down in the column, and besides if the movements were limited to this area alone they should be quite appreciable, just as those of the fontanelle in the child, or where there is a gap in the skull of an adult. Of course it is impossible, from the position of the sub-occipital ligament, to shew by means of a window, that such a movement does not take place when the parts are intact; but the writer believes that this experiment shews that distension of the dura lower down in the cord does not take place with expiration, and therefore that no fluid passes down there from the brain, and for the reasons given above it is extremely improbable that any such movement occurs opposite the occipito-atlantal membrane, so long as the supervening muscles and aponeuroses are not reflected.

Here, again, however it appeared to the writer that experiments by means of injection of coloured particles in fine suspension into the subarachnoid space would demonstrate in another manner whether any such movement as has been alleged to take place, really does occur.

For that purpose, several experiments were performed on animals which will now be shortly described.

Other experiments of the writer

EXPERIMENT 6. Large rabbit was etherised, then an incision was made in the middle line in the lower cervical region, the muscles were reflected from one or two vertebrae, and then the needle of a syringe was inserted through the interspinal ligaments, and about 3 minims of Prussian blue in suspension in normal salt solution injected as the needle which had penetrated the column was being withdrawn. The animal lived about 10 minutes taking deep respirations, and was then killed by chloroform, put in ice and frozen sections made.

Here as in all the other experiments by injection, microscopical sections of the cord was made and examined under high and low power, so that not even the finest granules could be missed.

No movement of injection particles in the closed canal with respiration.

It was found that though some of the injection had been made into the column itself, and had passed along the central canal for some little distance, yet some was in the subarachnoid space, and beyond a distance of from $\frac{1}{2}$ to $\frac{3}{4}$ inch from the point of injection absolutely no granules could be seen in the subarachnoid space. The very slight diffusion seen here - about $\frac{1}{2}$ to $\frac{3}{4}$ inch from point of injection, is no doubt the result of the injection itself, and not of any respiratory movements of the fluid, for that some diffusion of granules takes place is what one would expect from the use of a hypodermic syringe, and is proved by experiment 7 about to be narrated, whilst if any movement occurred with the respirations, as the animal lived 10 minutes, and was taking deep respirations the granules should have been carried to some considerable distance.

Control experiment

<u>EXPERIMENT 7.</u> A control experiment; was carried out on a <u>dead</u> rabbit. As in the last experiment, (6) an incision was made in the middle line, the muscles reflected, and an injection of about

5 minims of Prussian blue, in fine suspension, made through the spinal ligaments into the spinal column, the needle being gradually withdrawn so that some of the granules should be left in the subarachnoid space. The body was then put in ice, frozen sections cut, and then microscopic sections of the cord made. Here as in Experiment 6, there was some diffusion fully ¾ in. from the point of injection, the direct result of the injection itself.

An even more complete and satisfactory proof than that afforded by Experiment 6, that no such flow of cerebro-spinal fluid occurs with the respiratory movements inside the spinal canal, was afforded by another experiment, also on a rabbit.

Another injection experiment

EXPERIMENT 8. Large black rabbit was etherised as usual, an incision over lower cervical region was made, and then the muscles were carefully reflected from the vertebrae, for a short distance, a very small trephine hole, (about ⅙ inch in diameter) was then made in the postero-lateral aspect of the spinal column, and then 4 or 5 minims of Prussian blue in suspension injected beneath the membranes. The muscles were then stitched back in position as far as possible. The operation was carried out under asceptic precautions, and the animal was afterwards put in a cage amongst wool, and with a hot bottle. It was quite lively and eating an hour or two after the operation, though there was some weakness of the hind legs. After living 54 hours after the operation, it was killed by chloroform, put in ice and frozen sections made as in the case of the others.

On examination the microscopic sections shewed that above the point of injection the granules did not reach further than from $\frac{1}{2}$ to $\frac{3}{4}$ of an inch, whilst downwards they reached $1\frac{1}{2}$ to 2 inches or so below the point of injection.

This experiment seems to the writer to be most convincing, for had there been movement of cerebro-spinal fluid, the diffusion would have been both above and below the point of injection. On the contrary, however, there had been <u>no flow upwards</u>, for as has been already shewn diffusion to $\frac{1}{2}$ inch or so occurs from the mere injection, whilst the flow downwards, which is not by any means so great as one would have expected had it been due to the influence of respiration going on for fully 2 days, is almost certainly only the result of the natural flow of the cerebro-spinal fluid, which being secreted in the choroid plexuses passes partly down the cord. This experiment also seems to shew that this normal flow of fluid is a comparatively slow one, the granules having been carried not more than 2 inches in 2 days. It was also found that in none of the sections were there any granules in the sheaths of the nerves, not even in the nerves close to the point of injection. This shews that there is no flow along the nerve sheaths either, with the respiratory movements, else one would have had undoubtedly some of the granules carried with the fluid along the sheaths of the nerves close to the point of injection.

EXPERIMENT 9. Another experiment, though less successful, ought to be briefly referred to. It was carried out on the dog of experiment 5. After the window had been unscrewed from the spinal column, several minims of Prussian blue in suspension were injected beneath the membranes, then the opening of the trephine plugged by a tightly fitting cork, and after 10 - 15 minutes, the dog was killed by chloroform, and frozen sections made in the usual way.

In this case it was found that there had been considerable haemorrhage into the subarachnoid space, probably from the puncture of a vessel in the membranes, which had carried the granules to some distance, 1 inch fully, from the point of inoculation. All the granules however, were in the blood clot, none beyond, shewing that the haemorrhage was the cause of the diffusion of the granules in this experiment.

This haemorrhage is occasionally troublesome, for in another case of injection, in this case in the cranium, the writer found on making sections that there had been a considerable amount of bleeding into the subarachnoid space, which had carried the granules some distance. All cases where haemorrhage into the subarachnoid space occurs from the injection, are therefore unreliable as a guide of the amount of diffusion of the granules.

These experiments (5, 6, and 8) seem to the writer to prove that no appreciable flow of cerebro-spinal fluid takes place inside the spinal column, with the respiratory movements, and it would be practically impossible to imagine that any such flow could occur inside the cranium.

Experiments prove that there is practically no movement of particles in spinal subarachnoid space with respiration.

Some experiments however, were performed with Prussian blue on the cranium also as well as on the spinal column.

EXPERIMENT 10. Black rabbit was etherised, a crescentic incision was made over the vertex of the cranium, the flap reflected, bone exposed, and then by a fine drill driven by a catgut bow a hole just large enough to admit the point of a hypodermic syringe, was made in the cranium. Through this opening 3 minims of Prussian blue in fine suspension was made, the point of the needle being inserted into the brain, and the injection made as the needle was gradually withdrawn. The finger was then placed over this opening for 10 minutes, and then the animal was killed by chloroform, put in ice, and frozen sections made. These were decalcified with Perenni's fluid, and microscopic sections made. There was found no diffusion of the granules beyond $\frac{1}{4}$ in. or so.

Injection experiments of writer into cranial subarachnoid space

EXPERIMENT 11. Rabbit etherised, trephine opening made in the cranium, then several (4 or 5) minims of Prussian blue in suspension injected. The opening was then closed by closely fitting disc. The operation was done aseptically, but the animal only lived for 5 hours; after death it was put in ice, and sections were made. Here again there was no diffusion beyond $\frac{1}{4}$ inch or so, from the point of injection.

All these injection experiments go to prove then, that with the respiratory movements there is no appreciable flow, to and fro, of the cerebro-spinal fluid, either inside the cranium, or in the spinal cavity. How are we to account then, for the results of Quincke's (27) experiments already referred to in a previous part of the Thesis? One is certainly astonished to learn that the granules he used, were found so widely diffused, but in considering his results several circumstances must be taken into account.

No appreciable movement of granules in subarachnoid space of brain with respiration

The first of these is that in most of his experiments, the animals were not killed for weeks after the injection, and then of course one is not astonished to find their granules pretty widely scattered, through the natural flow of the cerebro-spinal fluid, apart altogether from the influence of respiration. In a few of the cases, however, the animals died within 24 - 48 hours, of the operation, and even in them the granules were widely diffused. It seems to the writer that the chief explanation of this lies, probably, in the method of removal of the central nervous system. Quincke does not state how he removed it, so that we may take it for granted that he did not take steps to fix the granules in the position they were in, at the time of death, and one can readily understand how with the manipulations necessary to remove the

Quincke's injection experiments.

Probable explanation of his results.

brain and spinal cord, the granules could be, and would almost certainly be, carried to a considerable distance by the movements imparted to the fluid in the removal. Any results then, from injection experiments, can only be trusted when the granules are fixed in the position they occupy at the time of death. This is insured by moving the body as little as possible, by putting it in ice, and then making frozen sections. After this the various parts can be examined microscopically.

Another point of great importance is the quantity of Prussian blue in suspension injected. Especially is this of importance when operating on such small animals as rabbits. It will be readily understood, when one remembers how small the sub-arachnoid space in such an animal is, that the injection of any great quantity of fluid will, by the mere act of injecting, carry granules to a considerable distance. There is the very greatest difference in using m. 10, from using m. 2 or 3, and in all his later experiments, and in practically all those here cited, the writer used only m. 3 or little more. So too the force used in injecting, is of importance, for if any more force than is absolutely necessary be used, the injection is readily carried to a considerable distance.

The injection must not be large.

Nor too much force used.

Experiment to shew this

The writer was able to shew this very clearly in the following experiment:-

EXPERIMENT 12. A rabbit was etherised, a semilunar flap reflected from the cranium, a fine hole drilled by the drill already mentioned, in Experiment 10, just large enough to admit the needle of the syringe. He then injected about 20 to 25 minims of carmine coloured gelatine, with some force into the subarachnoid space, the animal was immediately killed by chloroform, the body put in ice, and frozen sections made as in the other experiments. On examination it was found that the gelatine had passed at least $\frac{2}{3}$ down the whole length of the cord, as well as through the aqueduct of Sylvius into the lateral ventricles.

Quincke in his experiments ~~used~~ (which it must be stated however, were all on dogs) used 1. c.c. for an injection, which is certainly more than there is any necessity for. Still this is not relatively a very large amount to be added to the cerebro-spinal fluid of a dog, and the writer thinks therefore, that the results he got in the animals examined soon after injection i.e. 24 - 48 hours or so, must be sought in a diffusion of the granules during the extraction of the brain and cord.

The results of the experiments already given in detail in relation to this question of the movement of the cerebro-spinal fluid with respiration may be summed up thus.

Foregoing experiments prove that there is no movement of the brain or spinal cord when the atmospheric pressure is cut off

1. That although movements of the membranes of the brain, and of the membranes of the cord, with respiration are quite distinct after trephining the cranium and spinal column respectively, these movements are no longer seen after a window has been screwed into the opening, and the atmospheric pressure in this way has been cut off from the intra-cranial, or intra-spinal contents.

And that there is no movement of particles in the subarachnoid space of brain or cord with respiration.

2. That when injections of coloured particles are made into the subarachnoid space of the cranium, or of the spinal cavity, interfering as little as possible with the normal condition of affairs, and then the animal allowed to live under an anaesthetic for $\frac{1}{4}$ hour, or more, taking deep respirations, no movement of the granules beyond the slight diffusion caused by the injection is found. This applies both to the dog and the rabbit.

3. Further that in the rabbit at least, the animal may live for hours, and even for days after the injection without any further movement of the granules, than an extremely small one, the result of the normal flow of the fluid; in the spinal column this seems to be almost wholly downwards.

The writer had no licence to allow him to keep dogs alive after coming out of anaesthesia, and so could not carry out these experiments on them.

From the above one is completely justified, the writer thinks, in asserting that under normal physiological conditions no flow of cerebro-spinal fluid results from the respiratory movements.

(c) Having seen then, that with the respiratory movements there is probably no flow of blood from spinal venous plexuses to the cranial venous sinuses, nor flow of cerebro-spinal fluid from the spinal cavity to the cranium, nor flow of fluid along the nerve sheaths of the cranial or spinal nerves, we must next consider whether the place of the blood aspirated from the cranial veins during inspiration is not taken by arterial blood, the intracranial arteries becoming distended during that period.

Do the intra-cranial arteries distend during inspiration?

It seems quite impossible with any method at present known, to directly determine this, but one can at least discuss the probability of such a distension of the arteries inside the skull (during inspiration.)

That the arteries of the brain very readily alter in diameter, has been already shewn in the consideration of the circulation in the unclosed skull, indeed that they alter under very slight variations in pressure. We have seen that all ordinary sensory stimuli cause a distinct increase in the size of the intra-cranial vessels, whilst the arteries in the rest of the body are contracted, the contraction of the latter, and consequent rise of arterial pressure being undoubtedly the cause of the distension of the former. So when the vessels of an arm are dilated by putting it in hot water, the vessels of the brain contract, no doubt because of the lowering of the arterial pressure so produced. This extreme sensitiveness of the arteries of the brain to the condition of the arteries in the rest of the body, or in part of the body, will be considered at greater length further on, but all that it is desired to emphasise at present is, that the arteries of the brain <u>do very readily alter in calibre</u>.

Arguments in favour of this theory.

During the inspiratory act, the veins inside the cranium except those with rigid walls, i.e. the cranial sinuses, must undoubtedly contract from the aspiration of the venous blood. Along with this contraction of the veins there is a lowering of the cerebro-spinal pressure. At the same time that this cerebro-spinal pressure is lessened, the arterial pressure throughout the body generally rises, for with inspiration there is, of course, rise of intra-arterial pressure, and it is quite evident that such a state of affairs must almost certainly lead to dilatation of the intra-~~arterial~~ cranial arteries for the support to their walls being lessened, and the pressure inside being greater, dilatation is a necessary result unless the muscular coat of the artery should be put into a state of contraction during the inspiratory period, a supposition for which there is not the faintest foundation.

As the arterial area inside the skull must in this way be considerably increased especially during the earlier part of the inspiratory period, there will probably be a more rapid flow of blood along the carotids at this time than along the other arteries of the upper part of the body, which so far as the <u>direct</u> influence of the respiratory movements are concerned, are under similar influences.

No actual proof possible at present.

It seems to the writer however, impossible to test this experimentally, for the rate of flow would require to be calculated inside the arteries without allowing entrance of the atmosphere. Probably then during inspiration the rate of flow along the carotid artery is greater than that along the subclavian let us say, whilst during expiration, the condition of the veins, and the cerebro-spinal pressure being affected in a directly opposite direction, the rate of flow along the carotid is probably less than that along the subclavian.

Rate of flow along carotid probably more rapid than along other arteries during inspiration.

But although the rate of flow along the carotid is probably increased during inspiration, and decreased during expiration, relatively to the other arteries it does not at all necessarily follow that the rate of flow through the capillaries of the brain varies. Indeed it is inconceivable that such constant variations in the rate of capillary flow in the brain should exist. All that happens probably is that during inspiration the arteries become distended, when the veins are smaller, whilst during expiration they become smaller when the veins are distended: and the rate of capillary flow remains practically constant.

It must be at once admitted that there is no proof that such a distension of the arteries does occur, and the writer cannot think of any means by which the question can be settled, but for the reasons already set forth, he fails to see in what other manner the place of the venous blood aspirated during inspiration, can be taken, and all the conditions present are, he thinks, such as would lead to this dilatation of the arteries, and to the place of the venous blood being taken by arterial blood.

II. Effect of the arterial pulsation on the intracranial circulation in the closed skull.

The other chief cause of the changes in the intracranial circulation beside respiration, is the arterial pulsation.

Effects of arterial pulsation on the intracranial circulation.

It will not be necessary in discussing the influence of the arterial pulsation in the closed skull to enter at any great length into the possible results on the various fluids inside the cerebrospinal cavity, as much of the argument advanced when discussing the influence of respiration holds good here.

With each heart beat the arteries of the brain in the unclosed skull pulsate as in the rest of the body, and this pulsation must also occur in the closed skull. As we have already seen, in all experiments where a window has been fixed in the cranium, or in the spinal column, pulsation of the arteries continues as before the window was inserted. This has frequently been accepted as a proof that the quantity of blood inside the cranium can vary, but that deduction is not quite justified, for here as during the respiratory movements, distension of the vessels of one side of the circulation

Is the quantity of blood inside the cranium increased by the arterial pulsation?

(arterial) may be accompanied by diminution in the size of the vessels of the other side of the circulation (venous) and vice versa.

To follow, however, the method adopted in considering the change produced by respiration. The extra space occupied by the arteries during pulsation must be got at the expense of (a) either cerebro-spinal fluid, or (b) venous blood.

(a) Cerebro-spinal fluid. It has been suggested that during arterial pulsation, cerebro-spinal fluid is pressed from cranial cavity into the spinal cavity where accommodation is found for it. But here again the conditions in the spinal cavity are the same as those in the cranial cavity, for the intra-spinal arteries are also pulsating, and unless the spinal ligaments then distend, or fluid flows along the sheaths of the nerves, or fat and other extra dural tissue is pressed out through the inter-vertebral foramina, no movement of fluid as suggested can occur. We have already seen the reasons why in all probability such phenomena do not occur during respiration, and for similar reasons it is extremely unlikely that they occur with arterial pulsation.

Is there movement of the cerebro-spinal fluid with the arterial pulsation?

Reasons why there is probably no such movement of cerebro-spinal fluid.

The experiment of François-Franck, (42) in which a fine haemodromometer was inserted through the sub-occipital ligament, and which he thought proved that flow of cerebro-spinal fluid occured from the cranial to the spinal cavity with the arterial pulsation, has been already referred to. We need only repeat here that it is far from convincing, because it seems impossible that one could be sure of the end of the instrument being in the subarachnoid space, without touching the cord, or an artery of the membranes, which might readily enough communicate such a movement to the instrument, as was observed.

Franck's experiment and its probable fallacy.

Besides, the various experiments of the writer's* already referred to, where injections of Prussian blue in suspension were injected into the subarachnoid space, seem to prove that such a movement does not occur.

(b) As then, probably no flow of cerebro-spinal fluid takes place during arterial pulsation, one must naturally look to the venous side of the intra-cranial circulation for the explanation of how the arterial pulsation is permitted.

Pulsation of the intra-cranial veins with the arterial pulsation.

Long ago Carson(9) suggested that with each arterial pulsation blood must be pressed from the veins inside the skull, and although since then the discovery of the cerebro-spinal fluid has rendered the subject much more intricate, the writer is inclined to agree with him. What evidence is there in favour of this view? It has frequently been observed in opening veins at the base of the skull, that the blood spouted from them synchronously with the arterial beat. Moreover, Mosso (37) found that after inserting a cannula into an intra-cranial sinus of a dog, and covering the trephine opening with a rigid plate, that there were present pulsations synchronous with the arterial pulsations. Although it might be said that the pulsations seen were due to pulsation of the brain round the sinus affecting the cannula, without actually proving that flow of blood along the sinuses occurs with the arterial beats, the following observation seems to prove that such a flow does occur.

Observations shewing this.

Observation 1. A boy aged 8 years with symptoms of intracranial mischief following an otitis media, was operated on by Dr Burn Murdoch in the summer of 1894. After the mastoid antrum had been opened into, and nothing abnormal found there, the lateral sinus was exposed. It also was found healthy, and pulsating, and it was noticed by the writer as well as by the others present, that there was pulsation in the sinus synchronous with the arterial pulsation. Considering the position of the sinus, one cannot believe that this could be

Observation of writer shewing presence of pulsation in cerebral sinus, with arterial pulsation.

due to brain pulsation, and one is perfectly justified therefore in considering that it was due to the propulsion of venous blood along the sinus consequent on the arterial pulsation inside the skull. The case, it may be mentioned, proved to be one of suppurative meningitis, although none of the foci of suppuration were in relation to the lateral sinus. The intracranial pressure was, however, undoubtedly high.

Here then is a case proving that with heightened intracranial pressure, increased flow of venous blood along the sinuses during the arterial pulsation does occur, and it is extremely probable that under ordinary physiological conditions a similar increased flow occurs.

The arteries then, in all probability, exert a lateral pressure on the veins, causing compression of them, and consequently increased venous flow from the skull, as well as the ordinary <u>vis a tergo</u> action.

Large veins flowing into the sinuses are probably compressed by arterial pulsation.

At what point in the venous system does this compression occur? As the pressure inside the veins lessens as you pass from capillaries, through the small veins to the large ones, one would expect that the largest ones would become compressed. But as the sinuses have very incompressible walls in all probability it is the large veins which empty into the sinuses which give way before the arterial pulsation.

To repeat then, with each heart beat there is arterial pulsation inside the skull. With this, however, there is probably no flow of cerebro-spinal fluid worth mentioning, because of the conditions inside the spinal column being similar to those inside the brain. The expansion of the arteries occurs at the expense of the veins, the large veins flowing into the cerebral sinuses being compressed, and an increased flow of venous blood from the skull occuring with each arterial pulsation.

In the spinal column, a similar compression of the veins probably occurs, but as here the sinuses have not rigid walls, the largest ones are those which one would naturally expect to be those compressed.

Method of Regulation of Calibre of Intracranial Arteries.

In considering the question of the circulation of the brain, one cannot help being struck with its remarkable sensitiveness to the state of the circulation in the rest of the body; or as it might be put, one is astonished to find how completely its circulation is at the mercy of the general circulation. Of course the circulation of one part of the body is dependent more or less on the circulation in the rest, but this applies much more forcibly to the brain than to any other organ, even than to those organs which in their great vascular supply somewhat resemble it.

Regulation of calibre of intracranial arteries.

Circulation of the brain largely at the mercy of the general circulation

We have already more than once noticed how the arteries of the brain become distended when the general arterial pressure rises, and how they become contracted when the vessels of other parts are distended. Thus in the conditions of the circulation when Traube-Hering curves set in, whilst the other organs e.g. the kidney, contract synchronously with the rise of arterial pressure the brain distends in other words, whilst evidently from a stimulus from the vaso-motor centre the arteries in all other parts of the body become contracted those in the brain undergo dilatation. This peculiar behaviour on the part of the intracranial vessels has led to a considerable amount of investigation as to the question of a vaso-motor nerve supply to them. Roy and Sherrington (49) and more recently Bayliss and Hill (68), who have made many experiments to elucidate this point, both come to the conclusion that there is no evidence of the presence of such nerves. The former found that in all conditions investigated (and they were numerous) the expansion of the brain exactly corresponded with the condition of the general arterial and venous pressure, except in the case where acids were injected into the circulation, when there was a great 'active' dilatation without any corresponding effect on the general circulation, and this dilatation they thought was probably due to the direct action of the circulating lymph in the muscular fibres of the veins. Bayliss and Hill (68) more recently investigating by different methods, have found that even in this case there is no alteration in the intracranial circulation without a corresponding change in the general circulation. They found, in fact, that with any rise of general arterial, or general venous pressure the cerebro-spinal pressure rose, and with any fall of general arterial, or general venous pressure, it fell; but that alterations in the general venous pressure affected it

Is there a vaso-motor nerve supply to the arteries of the brain?

Experiments of Roy and Sherrington.

Experiments of Bayliss and Hill.

more readily than alterations in the general arterial pressure, and that without a single exception. They conclude therefore, that all variations in intracranial pressure are passive, and they think that variations in it are chiefly brought about by alterations in the splanchnic venous area. Their work is extremely valuable, and there can be no doubt that as a rule, the intracranial circulation is <u>entirely</u> dependent on the circulation of the body generally. It is extremely difficult to imagine however, that the congestion, which as we have seen is present in the brain during mental work of various kinds, and the congestion which is almost certainly present in the motor areas when movements are being performed, is only passive in character. As we have seen, during mental effort there is marked expansion of the brain in the unclosed skull, evidently from dilatation of the arteries, and no doubt in the closed skull a similar distension of the arteries occurs. Although at the same time there is a diminution in the volume of the limbs, as Mosso has shewn by the plethysmograph, and also a rise of general arterial pressure, one could scarcely consider it likely that the congestion of the brain then present is brought about indirectly by a vaso-motor stimulation, causing contraction of the vessels of the

No proof of any vaso-motor nerve supply.

limbs, and so general rise of arterial pressure. That this explanation is within the range of possibility may be granted, but when it is remembered that frequently, as was to be expected, and as has been observed during intracranial operations, the congestion is limited to certain regions of the brain only, (53) the explanation seems to the writer to completely collapse.

Probably arteries of the brain are not entirely dependent on the circulation of the body generally.

Besides, if the arteries of the brain acted only in this passive way, there would practically be no necessity for a muscular coat at all. There is, however, a very distinct muscular coat, which, in certain diseases where there are probably frequent variations in the circulation of parts of the brain, gets remarkably hypertrophied, shewing that it is an active muscular coat. This activity of the muscular coat of the intracranial arteries is even better shewn by a glance at the tracings (figs. 30 and 33) given in the first part of the Thesis, from the girl with the persistent fontanelle.

The muscular coat of the arteries of the brain is active.

There it will be seen that after the inhalation of nitrite of amyl by the girl, the tracings of the fontanelle rise markedly, shewing that the arteries of the brain are then distended. But if they always responded passively to the condition of the of the circulation elsewhere, they should rather

Proof of this.

contract, for the arteries in the rest of the body are dilated and there is a consequent marked fall of arterial pressure.

In this case it is practically certain that there is a direct action of the drug on the vessels of the brain, and under the circumstances where there is a local dilatation of the vessels of one region of the brain during the functional activity of that part, it is inconceivable that such a dilatation could be anything else than active i.e. independent of the circulation in the body generally.

How this active dilatation is brought about, is at present quite unknown, for as has been said, there is not the slightest evidence of any nerves from the general vaso-motor centre regulating the calibre of the vessels, although very numerous and persistent efforts towards the discovery of such, have been made. Nor does the action of the nitrite of amyl in dilating the intracranial arteries, lessen in any way the strength of the evidence against the existence of any vaso-motor nerves from the general vaso-motor centre, for it has been shewn that the action of amyl nitrite is chiefly peripheral, and probably exerted on the muscular walls of the vessels themselves (75). Thus if all the nerves to a part of the body be divided, and if in addition the spinal cord high up in the cervical region, be divided, and all fibres from the vaso-motor centre thus cut off from the part of the body under observation,, the blood vessels of that part still dilate when amyl nitrite is blown on the lungs.

Arteries of brain are, however, probably not under the control of the general vaso-motor centre.

There are various circumstances, moreover, e.g. the behaviour of the cerebral vessels as compared with the vessels of all the other parts of the body during Traube-Hering waves in the circulation, which seems to suggest, apart from any negative evidence, that they are not supplied from the general vaso-motor centre. Whether there is some other centre or centres for regulating of the calibre of the vessels of the brain, or whether the muscular coat is directly acted on by the lymph surrounding the vessels, as Roy and Sherrington (49) have suggested, it seems useless at present to surmise, although to the writer the former suggestion, vague though it be, appears to be the more probable one.

IV. THE INTRACRANIAL CIRCULATION UNDER SOME PATHOLOGICAL CONDITIONS.

Hitherto we have been considering the intracranial circulation under ordinary physiological conditions: it is proposed to refer briefly in this section to a few pathological conditions to which the writer's tracings and experiments more or less directly bear reference.

Some pathological aspects of the intracranial circulation.

It has been shewn that normally, practically no movement of cerebro-spinal fluid occurs with expiration or with arterial pulsation, for although during expiration there is a rise of intracranial pressure in the skull, a similar rise of pressure occurs inside the spinal column and so no movement of fluid takes place.

What happens when a pathological rise of pressure occurs inside the skull? One may take as an example of such a rise of pressure an effusion of blood inside the cranium, say, on the surface of the brain. In this case the effusion of blood causes, of course, an increase in the intracranial pressure. As there is a free communication between the cerebro-spinal fluid in the cranial cavity and the fluid in the spinal cavity the increase of pressure is transmitted to the spinal cavity also. With the increased intracranial and intraspinal pressure there is a certain amount of compression of the veins, as the general intracranial subarachnoid pressure which is usually the same as the intracranial venous pressure must now be greater than the latter. In the case of the brain this occurs probably in the large veins opening into the venous Sinuses - in the spinal cavity in the largest venous sinuses. This compression of the spinal sinuses which results from the transmitted increase in intracranial pressure and depends in its extent, on the amount of that pressure, naturally tends to lessen the quantity of blood inside the spinal column and so allows of a certain amount of fluid to flow from the cranial to the spinal cavity. The flow of fluid from the cranial to the spinal cavity is of great importance, for it permits a much larger effusion of blood to occur without interfering with the intracranial circulation, than would be possible were the cranial cavity completely cut off from the spinal cavity.

Reasons for thinking there is flow of cerebro-spinal fluid into the spinal cavity with rise of intracranial pressure.

If the effusion of blood still continues however the respite granted to the intracranial circulation by the flow of fluid into the spinal cavity, is not sufficient to ward off grave alterations in the circulation within the skull.

For with the increasing pressure the veins both of the brain and of the spinal cavity are becoming more and more compressed and eventually the compression reaches such an extent that the diameter of the veins is not so great as that of the arteries. When this point is reached, the intracranial circulation is in a very grave condition - for the necessary result is that at first there is venous congestion of the capillaries from the obstruction to the venous outflow caused by the increase of pressure, the rate of flow through the capillaries is greatly retarded so that the brain does not receive a proper nutritive supply.

But as the venous outflow is so retarded the intracranial pressure rises higher and higher - blood still being conveyed to the brain by the arteries - and so the large veins become absolutely compressed, and then the small veins, the capillaries and the arterioles respectively, as the intracranial pressure rises to the level of the pressure inside the veins, capillaries and arterioles. When these later stages are reached the brain is in an anaemic condition, instead of the state of venous congestion present when the intracranial circulation becomes first greatly disturbed by the compression of the veins beyond the limit of a steady circulation - this limit as has been said, being that when the area of venous outflow becomes less than the area of arterial inflow.

Arguing then, theoretically as above we would expect a flow of cerebro-spinal fluid from the cranium to the spinal cavity, when from any cause the pressure inside the skull becomes increased, without there being a similar cause of rise of intraspinal pressure The writer resolved to determine this experimentally and therefore the following experiment was performed.

Experiment of writer to prove this.

Experiment 13. A rabbit was etherised - an incision made over the upper dorsal region the muscles reflected and through the spinal ligament about three minims of Prussian blue in suspension were injected into the spinal subarachnoid space. Then a semilunar incision having been made over the cranium, and a fine opening made by a drill just sufficiently large to admit the needle of a hyperdermic syringe, an injection of about 20 m of gelatine was made into the subarachnoid space on the surface of the brain - the animal was then chloroformed to death put in ice and frozen sections cut.

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On examination it was found that granules of Prussian blue had passed down almost to the lowest point of the spinal cord. In addition granules were seen along the sheaths of the nerves near the point of injection.

In this case of course the rise of intracranial pressure produced was very great.

This shews that under experimental conditions closely resembling the conditions present in an effusion on the surface of the brain a flow of cerebro-spinal fluid occurs from the cranial into the spinal cavity.

There can be little doubt that with other rises of intracranial pressure - e.g. a haemorrhage into the substance, depressed skull, etc., there is a similar flow of cerebro-spinal fluid from the cranial to the spinal cavity. Conversely when there is a rise of intra-spinal pressure from a haemorrhage into the cord, etc., there is probably a flow of cerebro-spinal fluid from the spinal column into the cranium.

Bayliss and Hill's views on movement of cerebro-spinal fluid during increase of intracranial pressure.

Although this flow of fluid undoubtedly occurs with these rises of intracranial pressure, Bayliss and Hill (68) assert that such a flow is comparatively slight - they shew that if the intra-spinal pressure be reckoned and also the intracranial and that then the intracranial be markedly increased, the intra-spinal rises correspondingly, but only for a very short period: it then stands still whilst the intracranial goes on rising more and more. They therefore hold that in pathological rises of intracranial pressure, only a little fluid flows from the skull into the spinal column and that then the brain sinks and the base plugs up the foramen magnum, so that there is no longer any communication between the fluid in the one cavity and the fluid in the other and consequently no further rise of pressure inside the spinal column.

Difference between sudden and gradual rises of intracranial pressure.

But granting that the intra-spinal pressure soon ceases to rise, it is quite apparent that this does not hold good for all rises of intracranial pressure. In fact only in very sudden rises of pressure as in haemorrhages, or depressed fractures would one expect this plugging of the foramen by the base of the brain to occur. In cases of gradual rise of pressure as in cases of cerebral tumour, etc., where the movement of fluid as the result of the difference of pressure in the two cavities would be extremely slow it is almost certain that no such descent of the base of the brain and plugging of the foramen magnum occurs - probably the intra-spinal pressure rises equally with the intracranial pressure in such cases.

In these gradual rises of intracranial pressure, and indeed in all rises of intracranial pressure except the very sudden, another point of great importance must be kept in mind. For with increased rise of pressure there is a tendency for an increased absorption of the cerebro-spinal fluid. Thus in some cases of intracranial tumour the quantity of cerebro-spinal fluid is decreased. This is not necessarily the case, of course, in all intracranial tumours for such a tumour may act in other ways as by interfering in some way with the channels of absorption of the fluid, or by causing increased secretion of fluid by pressing on certain veins.

In all cases of increased intracranial pressure then, the flow of cerebro-spinal fluid from the cranium into the spinal cavity depends largely on the rate of the increase. When the pressure is suddenly raised possibly a comparatively small quantity of fluid flows into the spinal cavity, further flow being prevented by the base of the brain sinking and plugging up the foramen magnum, as Bayliss and Hill suggest. On the other hand in very slow rises of intracranial pressure there is probably (unless there be local influences acting in an opposite direction, e.g. in tumours in certain positions) a very small quantity of fluid comparatively in the skull, whilst there is a large quantity inside the spinal column.

It is usually said that with increased pressure inside the brain from effusion, depressed fracture, tumour, etc.; there is a condition of cerebral anaemia. No doubt in many cases such a condition of anaemia exists, as seen p.m. but anaemia is not necessarily present and indeed as we have seen is probably never present in the first place. With the rise of pressure there is at first compression of the large veins, not of the capillaries and so the condition is one not of anaemia truly so called, but of venous congestion. There is a lessened flow through the capillaries, though the capillaries themselves are full. The tissues therefore are not oxidised and it is in such a condition that Geigel's term 'adiaemorrhysis' might be used. Later however, as whenever the stage of compression of the veins reaches such an extent that the area of the veins becomes less than that of the arteries, first the veins then the venules and then the capillaries become completely compressed and the condition becomes one of true anaemia, for now the capillaries are empty.

State of brain capillaries with rise of intracranial pressure.

It depends on the amount of the pressure there being first venous congestion and later, anaemia.

This is in all probablity the explanation of the apparent contradiction between the results for by Adamkiewicz and Dean. Both experimented by introducing foreign bodies inside the skull and noting the effect on the brain tissue. Whilst the former described congestion, the latter found marked anaemia and oedema. The explanation seems to the writer to lie in the fact that the foreign bodies introduced by Adamkiewicz were smaller than those used by Dean,

Reason for apparently antagonistic results of Adamkiewicz and Dean.

i.e. the intracranial rise of pressure was less and so whereas in his (Adamkiewicz's) experiments only the large veins were compressed causing venous congestion of the capillaries, in Dean's experiments the rise of pressure was so great as to compress the capillaries also.

Experiment 14. In an experiment carried out by the writer where a dog was trephined, a flat piece of glass inserted between dura and skull and then a window screwed air tight as in experiment 5. into the trephine hole there was distinct venous congestion. In such experiments of course the venous congestion is probably the result not of the general rise of the intracranial pressure but of the pressure of the foreign body on the veins of that part. As however here what follows is not capillary anaemia but venous congestion it is only reasonable to suppose that a similar result would occur through out the brain in a general rise of intracranial pressure.

It is not proposed here however to discuss the local effects of haemorrhages, tumours, etc. but only their effect in causing a general rise of intracranial pressure, and one may repeat that the increase of intracranial pressure without any synchronous primary rise in intra-spinal pressure causes flow of cerebro-spinal fluid from the cranium to the spinal cavity where accommodation is provided for it by compression of the spinal venous sinuses. If the pressure goes on increasing however, and after the large veins are compressed beyond a certain limit, there is produced venous congestion of the brain and later still with further rise of pressure, anaemia of the brain.

Hyperaemia of the brain.

HYPERAEMIA OF THE BRAIN. This term though much used is rather obscure. It is usually divided into passive congestion and active congestion, of the former there is no need to speak here, it is readily intelligible and frequently occurs; but it may be well to take a cursory glance at the latter, or at least at some of its forms. Gowers (54) (vol. II p.374 diseases of the nervous system) says, "in hyperaemia of the brain there is an increase in the amount of blood within its capillaries" and then he describes various forms of active hyperaemia amongst which appear, (1) over action of the heart (2) contractions of the arterioles elsewhere. Under these conditions there is undoubtedly increased intra-arterial pressure and the arteries will be more distended but what probably results is not a hyperaemia of the capillaries, but an increased flow through them, provided of course there is no obstruction to the venous return. If however the rise of arterial pressure should become excessive and the veins become as a result compressed then one would again have a condition of venous congestion of the capillaries. So that what is, at present, called active hyperaemia might either result in increased flow of blood through the capillaries - 'hyperdiamorrhysis of Geigel' - its usual result; or if very excessive might possibly result in a venous congestion of the capillaries from compression of the large veins.

Hyperaemia of brain may cause either hyper diaemorrhysis or adiaemorrhysis.

Anaemia of the brain. What is commonly known as anaemia of the brain is probably also not so much anaemia of the capillaries as a lessened flow through them. In a condition of syncope for example the heart acting very feebly sends less blood to the brain, the arterial pressure is lessened, the arteries are smaller. The arterial pressure is much less proportionately to the venous than what it was before, as a result less blood is forced out of the skull from the veins and the rate of flow from the arterial side through the capillaries to the venous is decreased.

Anaemia of the brain.

Two forms (a) with low intracranial pressure.

Another form of anaemia of the brain occurs with great rise of intracranial pressure causing compression not only of the veins but also of the capillaries - in this case also the flow through the

(b) with high intracranial pressure.

capillaries is interfered with: in the former, however, the intracranial pressure is lowered, in the latter it is greatly raised.

Apoplexy.

Apoplexy. The remarkable manner in which the intracranial vessels respond to any increase in the arterial pressure throughout the body explains very readily how apoplectic seizures so frequently follow strains of some kind: for with the strain there is necessarily rise of arterial pressure - there is a tendency for the vessels of the brain to distend and if they are much weakened by disease this is just the time when one would expect them to give way.

Cause of onset.

Miliary aneurisms.

Probably also the much greater amount of contraction and dilation of the arterial walls inside the skull which, as has been shewn probably occurs with arterial pulsation, and above all with respiratory movements and with increase of arterial tension, than in any arteries elsewhere in the body, helps to explain why miliary aneurisms are so common relatively in the vessels of the brain.

Probable reason for their frequency in the brain.

Treatment of intracranial haemorrhage.

Treatment of intracranial haemorrhage. Keeping in consideration the manner in which the intracranial circulation is carried on, we may with advantage take a glance at the best methods of treating intracranial haemorrhage. Absolute rest is obviously useful and necessary to prevent rise of arterial pressure with consequent dilation of the arteries of the brain. So are also the use of laxatives, diuretics and diaphoretics provided they have no action on the circulation which is contra-indicated. e.g. Digitalis would of course be strictly forbidden.

Bleeding obviously must be of service in reducing the arterial pressure inside the brain as elsewhere and so will tend to prevent further extravasation. In all probability arteriotomy is preferable to venesection, blood being drawn from the temporal artery which comes from the same trunk as the vessels to the brain: the effect would be more rapidly got.

The sensitiveness of the brain to the condition of the circulation elsewhere so frequently referred to already, at once suggests the use of means to cause dilation of the vessels of the extremities. Heat, in some form or other, rubefacients, etc., by dilating the vessels of the rest of the body undoubtedly greatly diminish the pressure in the arteries of the brain and so must be useful in the treatment of intracranial haemorrhage - this is probably by far the most effective treatment which can be adopted in intracranial haemorrhages. On the other hand amyl nitrite although it dilates the vessels of the rest of the body ought not to be used, as it also dilates the vessels inside the cranium, as has been already shewn in tracing.

The use of ice which is so common at present is very questionable to say the least of it. Any direct action of the cold applied outside the skull on the blood vessels inside the skull is at best very problematic, whilst the vaso constriction at the surface produced by the cold is distinctly disadvantageous, as it tends to produce a heightened arterial pressure with consequent dilatation of the arteries inside the skull. In all probability then ice ought to be avoided in intracranial haemorrhage.

S U M M A R Y.

From what has been said in the foregoing pages one is entitled, the writer thinks to make the following propositions regarding the intracranial circulation:-

1. The circulation in the closed skull differs greatly from that in the unclosed skull.

2. In both cases, however, the chief factors to be considered are the arterial pulsations, and the effects of the respiratory movements.

IN THE UNCLOSED SKULL.

3. In the open skull there are movements of the brain with both of these acts; that with the arterial pulsation, is due to the distension during systole of the arterioles which are very numerous in the brain.

4. The movements of the brain during respiration, consist in a distension of the brain with the expiratory movement, and a depression or contraction with the inspiratory movement.

5. The depression with the inspiratory movement is the result of the aspiratory action of that movement on the venous sinuses and veins of the brain.

6. This aspiratory act reduces the intravenous pressure so much that it falls beneath the weight of the column of blood from the brain to the heart. As the intracranial contents are open to the atmospheric pressure the result of this is that these vessels where the pressure is so lowered become compressed.

7. During the expiratory period on the other hand, the venous pressure is raised, because of interference with the flow of blood into the thorax. Consequently, no such compression of the intracranial veins occurs.

8. Thus the amount of blood inside the unclosed skull may vary within very great limits.

9. The depression of the brain, during ordinary respiration, corresponds very closely with the inspiratory act but when the inspiratory act is prolonged, there is a certain amount of distension of the brain towards the end of the act. The reason for this is of course that

the aspiratory action of the thorax has ceased towards the end of the inspiratory movement when so prolonged.

10. Similarly with expiration, when expiration is prolonged, there is a depression of the brain towards the end of the act.

11. Exaggerated respiratory movements cause a greater amount of movement of the brain. Even with the finest respiratory movements, however, there is a certain amount of distension and depression of the brain, if only one has fine enough instruments to record the movements.

12. The form of the pulse of the brain, is tricrotic, whether the tracing be taken by an instrument laid directly on the brain, or by a tracing taken through conducting tubes.

13. The pulse is usually anacrotic, but varies very greatly under various circumstances and is frequently katacrotic.

14. All rises of intracranial pressure may be divided into 2 classes. (1) active, and (2) passive.

15. In the former - the more uncommon - with the rise of intracranial pressure the individual pulse waves are higher, whilst they have also a tendency to become katacrotic. In this case the rise of intracranial pressure is from the arterial side.

16. In the passive form - with the rise of intracranial pressure the individual pulse waves are lower and more rounded, i.e., more anacrotic a type. In this case the rise of intracranial pressure is from the venous side. This is by far the more common form of rise of intracranial pressure.

17. The rise of intracranial pressure during expiration being from the venous side is passive in form - therefore the individual pulse waves are lower and more rounded. Results got to the opposite effect, viz., that during expiration the individual pulse waves are higher and during inspiration are lower (Binet and Sollier) are probably the result of the recording instrument not following the brain movements accurately.

18. All actions causing an interference with

the return of venous blood from the brain cause a passive rise of intracranial pressure. Thus movements of the head, crying, etc., cause a passive rise.

19. General movements cause a passive rise of intracranial pressure from raising the general venous pressure.

20. Holding one or both hands above the head causes a passive rise of pressure.

21. Lowering the head causes ~~an active~~ passive rise of intracranial pressure. Raising the head has the opposite effect.

22. An active rise of intracranial pressure would be produced by increased heart's action.

23. The most common form, however, of active rise of intracranial pressure is produced by mental activity. Thus all mental calculations are accompanied by such a rise.

All impressions on the organs of the senses are also accompanied by an active rise of intracranial pressure. Thus light objects held before patient, noises, etc., cause such a rise.

24. Accompanying such a rise there is a diminution of the volume of the limbs. The general arterial pressure is heightened (Mosso) Possibly also there is a diminution of the splanchnic venous area (Bayliss and Hill).

25. During the inhalation of nitrite of amyl, however, whilst the peripheral vessels are dilated and the arterial pressure is greatly reduced, there is a distension of the vessels of the brain also, similar to what occurs in active dilatation, i.e., the general level of the tracing rises and the individual pulse beats are higher and more katacrotic.

This shews that the walls of the arterioles inside the skull are also directly affected by the amyl nitrite.

26.. During sleep the intracranial tension is low and the pulse waves small, probably from arterial anaemia.

27.. In chloroform anaesthesia, a similar condition is seen.

28. When a patient awakes there is at once a rise in the intracranial pressure. There is a rise also when a patient comes out of

anaesthesia. The rise in both of these cases is an "active" rise.

IN THE CLOSED SKULL.

29. In the closed, as in the unclosed skull the venous side of the circulation is of the utmost importance and especially because of the remarkable influence of respiration on it, an influence which is even more important probably than in the unclosed skull. One must therefore in all considerations of the circulation in the closed skull keep prominently before him,

(a) The venous pressure (intracranial.)

(b) The influence of the respiratory movements. Exerted through the venous side of the circulation.)

30. In the closed skull the atmospheric pressure does not come into play - hence the great difference between the circulation to the closed, and that in the unclosed skull.

31. This applies in all probability to the spinal column as well as to the brain, for

practically speaking, in relation to the intraspinal circulation, the walls of the spinal column are non-distensile and therefore the spinal dura cannot be distended.

32. In ordinary physiological conditions, one should consider the cavities of the skull and of the spinal column as a single cavity.

33. With inspiration there is a lowering of the intracranial venous pressure, and of the intracranial (subarachnoid) pressure which follows the intracranial venous pressure.

34. As the vessels are not exposed, however, to atmospheric pressure, they do not become compressed with the fall of the intracranial venous pressure. This holds good both for the brain and for the spinal column, there is therefore no movement of the brain or of the spinal column with respiration, and therefore no movement of cerebro-spinal fluid worth mentioning.

35. So with the arterial pulsation, there is no movement of cerebro-spinal fluid and no pulsation of the brain and spinal column as a whole, although the arteries themselves of course pulsate.

36. When the arteries are distended as the result of the cardiac systole, the larger compressible veins are compressed and blood is forced from them. This lateral pressure exerted by the arteries leads to a pulsation in the cranial sinuses synchronous with the arterial pulse. This emptying of the larger veins to a greater or less degree takes place in the spinal column probably as well as in the cranium.

37. With the heart beats therefore the arteries become distended and the veins are compressed; between the beats the arteries contract and the veins again become dilated. The flow of blood throughout the capillaries, however, remains constant.

38. With inspiration when the blood is sucked from the veins their calibre is lessened, and there occurs probably a compensatory dilatation of the arteries; the flow of blood through the capillaries remains constant however. The result of this is, probably, that during inspiration the rate of flow of blood through the internal carotid is greater than through

the other arteries of large size above the diaphragm, which in other respects are under similar conditions. During expiration, on the other hand, it will be correspondingly slower than in the other arteries.

39. The first result of an increased arterial pressure would be an increased flow of blood through the capillaries. There would not be a larger quantity of blood inside the cranium.

40. In all variations of pressure affecting both the cranial and spinal cavities, there is no variation ~~to~~ in the quantity of blood present in the cavities. There is only either (a) a variation in the amount of blood in one side of the circulation, at the expense of the other e.g., in arterial at expense of the venous, or (b) an alteration in the rate of flow through the capillaries.

41. This (40) refers to sudden variations of pressure - variations lasting a considerable length of time may be accompanied by an alteration in the quantity of blood to these cavities from an alteration in an inverse direction of the quantity of cerebro-spinal fluid present.

42. Increase of pressure inside the cavities will cause first a compression of the veins to an extent corresponding to the amount of the increase of pressure. This compression occurs in the cranium in the veins which flow into the cranial sinuses, and in the spinal cavity in the larger veins. The intracranial sinuses themselves cannot be compressed because of their walls.

43. A certain amount of compression produces no very deleterious influence on the circulation but when a certain stage is reached - probably when the area of venous outflow becomes less than that of the arterial inflow, the circulation tends to become stagnant. The large veins, small veins, capillaries and arterioles successively become compressed and the pressure rises to that of the small veins, capillaries and arterioles respectively.

44. With the first onset of symptoms therefore the condition is probably not that of true aneamia, but of lessened flow because of venous congestion of the capillaries. Later however when the capillaries become compressed there ~~that~~ is true anaemia.

45. Increase of pressure in one cavity without corresponding primary rise of pressure in the other will be accompanied by a flow of fluid (cerebro-spinal) from that cavity to the other, because the pressure being transmitted will cause a compression of the veins in the other cavity, and so accommodation will be made for more fluid in it. Thus an intracranial haemorrhage will be accompanied by a flow of cerebro-spinal fluid into the spinal canal, whilst an intra-spinal haemorrhage will be accompanied by a flow of fluid into the cranial cavity.

46. In cases of intracranial rises of pressure, (general) the symptoms are probably chiefly due, not to the amount of pressure which may vary very greatly without causing symptoms (Bayliss and Hill) but to the state of the blood flow through the capillaries.

47. In nearly all conditions the intracranial circulation is directly dependent on the state of the circulation in other parts of the body.

48. In some conditions, however, as in inhalation of nitrite of amyl, and probably in certain mental conditions, this is not the case

and therefore though no evidence of vasomotor nerves can be got, and though probably the vessels of the brain are not supplied from the general vasomotor centre, there would appear to be a regulating mechanism of some kind that may be in the nature of a centre, or centres, higher up in the brain.

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72.	Wertheimer.	Archives de physiologie, Oct. 1895.
73.	Gauducheau and Bussière.	Comptes Rend: de la Société de Biologie. Nov. 29th, 1895.
74.	Campbell.	New York Med: Record. 1895. December, 7th.
75.	Binz.	Lectures on Pharmacology. New Sydenham Society. 1895. p. 150.

F I G U R E S.

Fig.1. Photograph of tracing taken with Marey's Sphygmograph of fontanelle of Girl - aged 18 months - lying asleep. It shews the anacrotic form of the pulse, and the respiratory undulations. This photograph is a little smaller than the actual tracing.

Fig.2. Photograph of tracing from fontanelle of a girl, E.M., aged 12 months, lying asleep. Shews anacrotic pulse and also the respiratory undulations. Taken with Marey's sphygmograph.

Fig.3. Part of tracing of fontanelle of boy,

R.C., aged 18 months lying awake. Taken with Marey's cardiograph and runs from right to left. Shews anacrotic form of pulse very well.

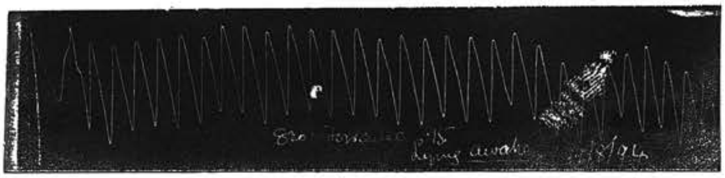

Fig.4. Photograph of tracing from fontanelle of boy, G.T., aged 15 months, lying awake. Fontanelle very lax and pulsations very distinct, but no 'cusps' to be seen on the pulse waves. These are absent only in cases where the intracranial pressure is very low. Taken with Marey's sphygmograph.

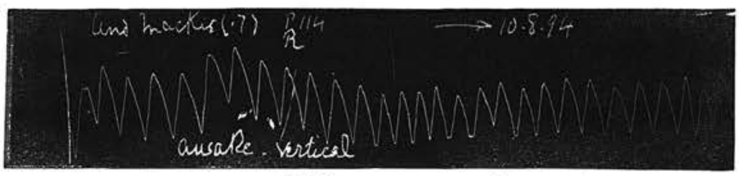

Fig.5. Photograph of fontanelle tracing of boy, A.M., aged 7 months, awake and held in vertical position. The form of pulsation shews low intracranial pressure. Taken with Marey's sphygmograph.

Fig.6. Photograph of fontanelle tracing from boy, R.McD., 10 months, lying asleep. Shews anacrotic form of pulse present as well in the sleeping as in the waking state. Taken with Marey's sphygmograph.

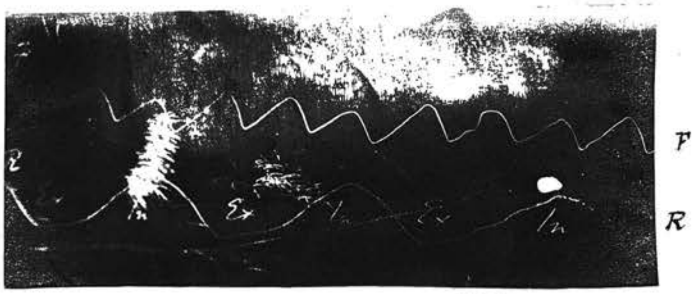

Fig.7. Photograph of fontanelle tracing(F) of a child, as well as a synchronous tracing of the respiratory movements(R).

The respiratory undulations on the fontanelle tracing are visible though not very distinct. Taken with Marey's cardiograph, considerably smaller than original tracing.

Fig.8. Photograph of synchronous tracings of the fontanelle and of the respiratory movements of a boy, W.M., age 7 months. The upper tracing is that of the fontanelle taken with Marey's cardiograph, the lower the respiratory tracing taken with the apparatus described at page . This photograph is much smaller than the original tracing, but it shews well the depression of the fontanelle with inspiration. At a. the levers got caught one on the other, so that they ran parallel for a few beats, but at b. got disentangled again. At c. they once more caught one on the other, but only for one respiratory period.

This boy was very emaciated when this tracing was taken.

Fig.9.

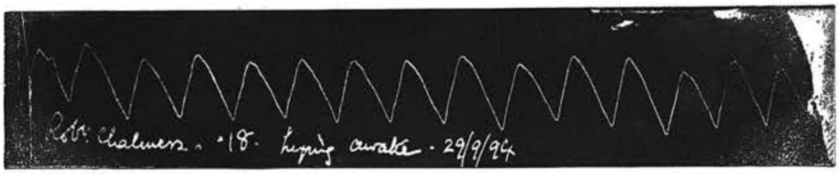

Fig.10.

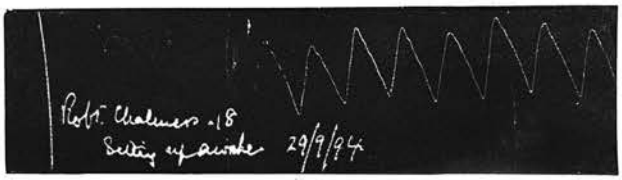

Fig.11.

Figs. 9, 10, and 11. Photographs of tracings from fontanelle of a boy R.C. aged 18 months. Taken with Marey's sphygmograph.

Fig.9 was taken when the child was lying asleep.

Fig.10 after he woke up, still lying quiet however.

Fig.11 propped up in sitting posture when awake.

The difference in the pulse in these three tracings is very marked - in fig.9 anacrotic and comparatively low; in fig.10. higher from "active" increase of pressure when a person awakes; and in fig. 11 still sharper and higher. Here (fig.11) the intracranial pressure is lower - a "passive" decrease of pressure with consequent increase in the height of the individual pulsations.

The differences in the intracranial pressure are not directly shewn by these tracings which are not continuous.

Fig.12.

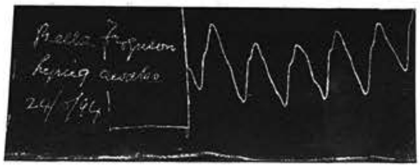

Fig.13

Figs.12 and 13. Photographs of fontanelle tracings of girl, B.F., aged 9 months. Fig.12, when lying asleep; Fig.13. when lying awake. They shew the greater amplitude of the pulsations in the waking state.

Taken with Marey's sphygmograph.

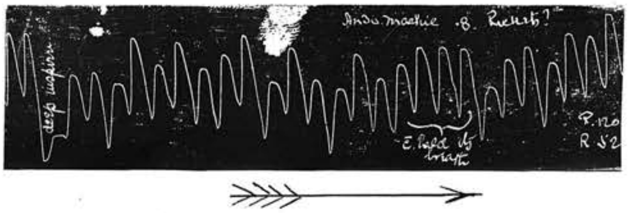

Fig.14. Tracing of fontanelle of boy, A.M., aged 9 months, shews the respiratory undulations. Also shews rise of intracranial pressure when the child held its breath.

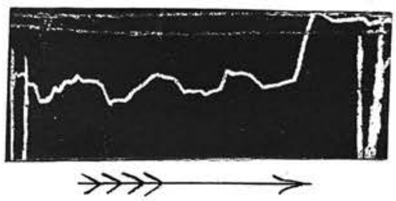

Fig.15. Photograph of tracing of fontanelle of child. After the sphygmograph was applied, the child which had been asleep wakened up with the noise of the instrument, and immediately the intracranial pressure rose, so that the lever left the paper.

Taken with a modified Dudgeon's sphygmograph.
Larger than the original tracing.

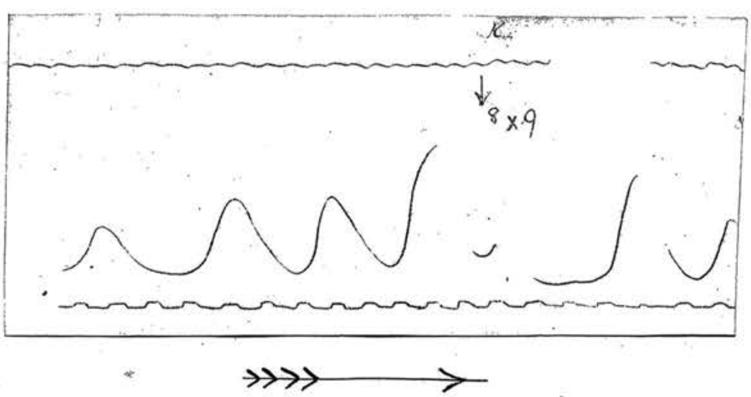

Fig.16. Photograph (much reduced) of tracing

from girl of 8 years with the persistent fontanelle referred to at page 5.

The upper line is the fontanelle tracing, the middle one the tracing of the respiratory movements, and the lower one that of the timing instrument (as in figs. 17. 18. 19. 20. 21. 30. 31 and 36).

A continuous tracing was being taken of the fontanelle when at ↓K her teacher asked her how much 8 x 9 was. Immediately the tracing rose and at the highest part of the rise the lever left the paper.

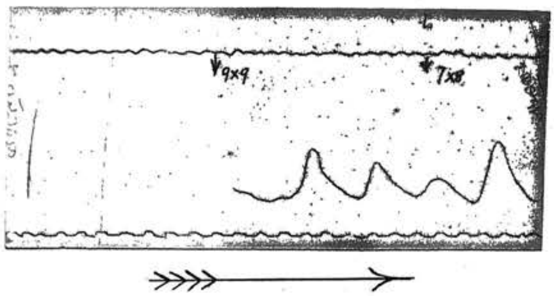

Fig.17. from same girl as fig.16. At the point marked 9 x 9 the teacher gave her this sum in mental arithmetic, and a rise in intracranial pressure was immediately seen. Similarly at the point marked 7 x 8.

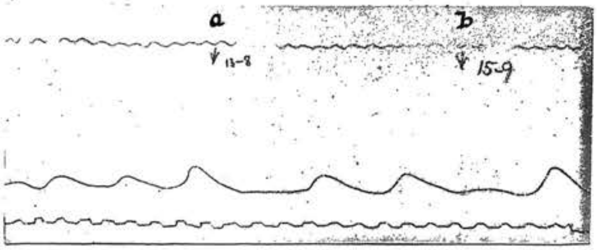

Fig.18. From same girl as figs.16 and 17.

Shews rise of intracranial pressure from mental calculations at ↓a and ↓b.

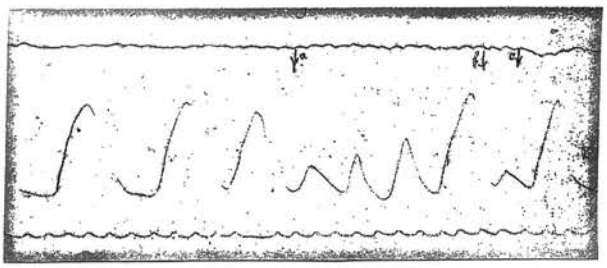

Fig.19. From same girl as figs.16, 17 and 18. Photograph much smaller than tracing; at ↓a. chocolate shewn to patient, at ↓b. name of chocolate asked, at ↓ answered "Fry". A distinct rise in the tracing is seen when the chocolate was shewn and after the answer the tracing fell.

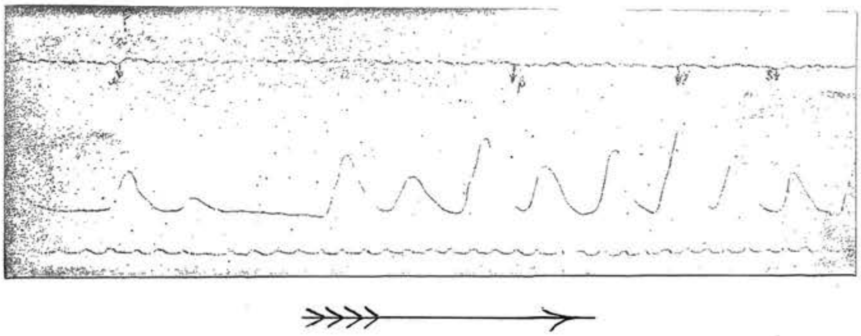

Fig.20. From same girl. Photograph much smaller than original tracing.

At ↓ α. a question in addition was given.

At ↓β. the girl answered the question.

At ↓ γ. another question in addition was given.

At ↓ δ. it was answered.

It will be seen that there is a rise in the level of the tracing when the mental activity, necessitated by the questions, was going on.

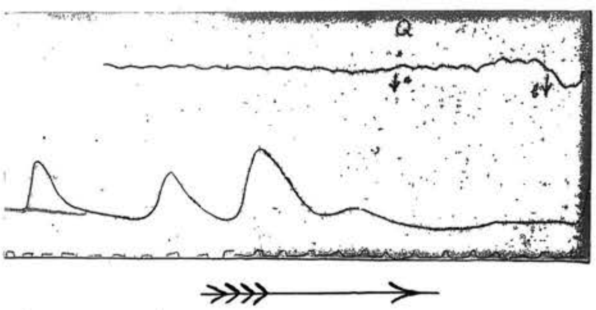

Fig.21. From same girl.

A continuous tracing was being taken when at ↓a. the head was gently pushed forwards. The result was a distinct rise in the tracing, no doubt from pressure on the veins of the neck. At ↓b. the head was gently pushed back to its original position, and the tracing which had been gradually rising higher and higher immediately fell.

Fig.22.

Fig.23.

Figs.22 and 23. Photographs of fontanelle tracing from a boy, G.T., aged 15 months. Taken with Marey's sphygmograph.

The tracings were taken just as patient was coming out of the influence of chloroform.

Fig.22. was taken when the boy was lying.

Fig.23. immediately afterwards, the boy being propped up in the sitting posture.

The change in the appearance of the pulse waves, from the alteration in posture is well seen.

Fig.24. Tracing of fontanelle of child taken with Marey's cardiograph. The tracing runs from right to left. The first part of the tracing (to the right) was taken with the child in the recumbent posture. At * the revolving drum was stopped, the child was held in the sitting posture, and then the rest of the tracing was taken. The marked difference in the form of the pulse waves in the erect from that in the recumbent posture is very well seen.

Unfortunately the lines are just a trifle faint.

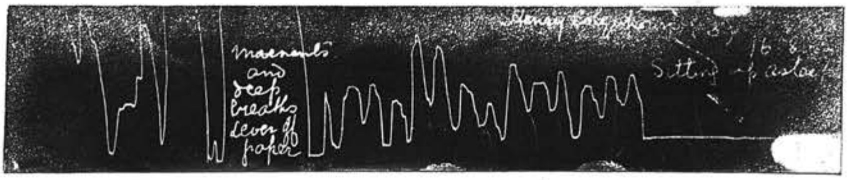

Fig.25. Photograph of fontanelle tracing of boy, H.C., aged 15 months, shews the effects of irregular and deep respirations on the movements of the fontanelle.

Taken with Marey's sphygmograph.

Fig.26. Photograph of fontanelle tracing from boy, G.T., aged 18 months, sitting up awake. Shews the effect of movements and deep and irregular respirations. Taken with Marey's sphygmograph.

Fig.27. Photograph of tracing from girl, R.V., aged 14 months. Shews the great rise of intracranial tension caused by crying, so that the lever soon

left the paper.

Taken with Marey's sphygmograph.

Fig.28.

Fig.29.

Figs. 28 and 29. Photographs of tracings from a baby 6 weeks old.

Fig.28. was taken when the child was deeply under chloroform. The individual pulsations are not very distinct, but the respiratory curves are marked - no doubt partly from a state of intracranial anaemia during the chloroform narcosis.

Fig.29. Taken when child was coming out of its influence. The respiratory undulations are not so great, though still well defined.

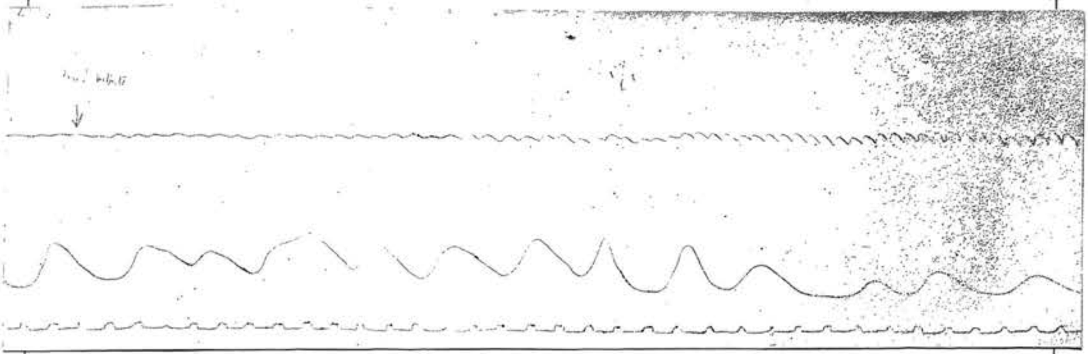

Fig.30. a.

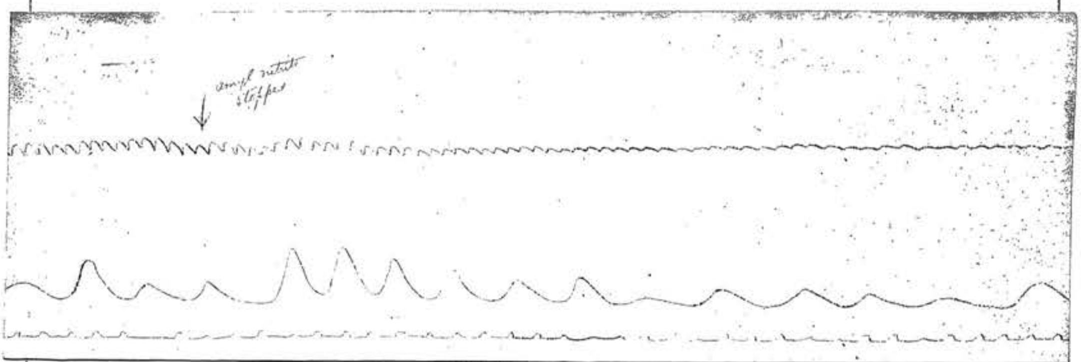

Fig.30. b.

Fig.30. Photograph of fontanelle tracing from the same girl as figs.16 to 21., photograph much smaller than the original tracing. A continuous tracing was being taken when at ↓ in fig.30.a. amyl nitrite was held before the girl's nose. Soon the level of the tracing began to rise and the individual pulse waves became more ample. The respiratory undulations also became more distinct. At ↓ in fig. 30.b. which is a continuation of fig.30.a. the amyl nitrite was removed and the tracing gradually returned to its state before the inhalation.

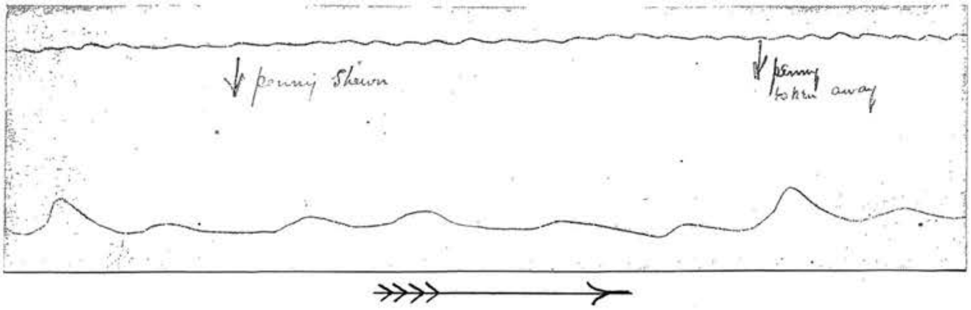

Fig.31. Photograph of fontanelle tracing from same girl as figs.16 to 21. Photograph much reduced from original tracing.

A continuous tracing was being taken when at ↓ a penny was shewn to her. There was a rise in the tracing shewing some mental effect thus produced. A little further on the penny was put away and the tracing again fell to the normal.

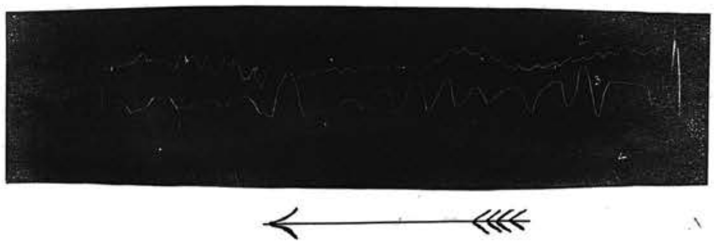

Fig.32. Photograph of fontanelle tracing from a boy, A.M., aged 8 months. Photograph very much smaller than original tracing, which was taken with Marey's cardiograph.

The upper line (2) is the fontanelle tracing.

The lower line (3) is the respiratory tracing.

The great irregularity of the tracing results from the fact that the child was sucking when the tracing was being taken. The irregularity of the respirations necessarily produced by sucking would largely tend to cause the irregularity of the fontanelle tracing.

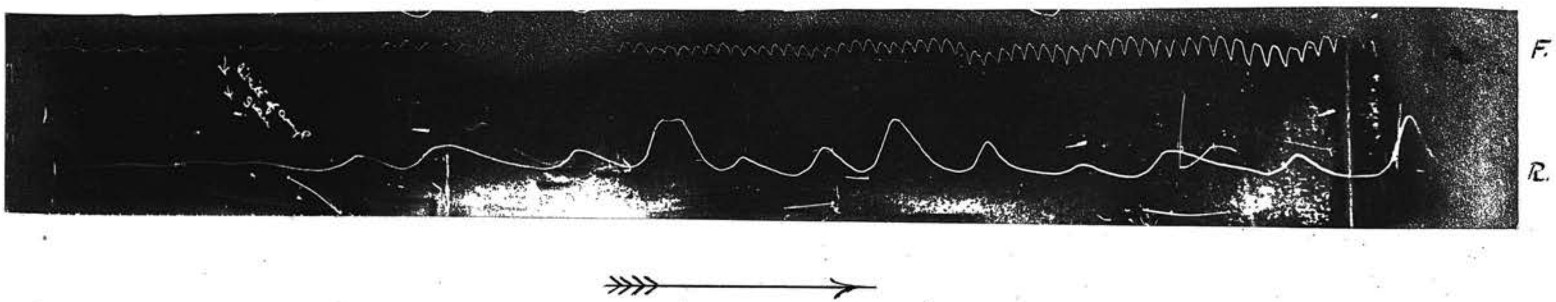

Fig.33. Photograph of tracing from girl of tracings 16 to 21., and of figs.30 and 31. Considerably smaller than original tracing. Taken with cardiograph.

The upper line (F) represents the fontanelle tracing.

The lower line (R). the respiratory movements.

After the inhalation of nitrite of amyl the fontanelle tracing rises markedly, the individual pulse waves are higher and become katacrotic, and the respiratory undulations are much more marked, although the respiratory movements remain much the same, (though not quite regular).

Soon after the nitrite of amyl begins to act, the pulse waves are also seen to become more rapid.

Fig.34.

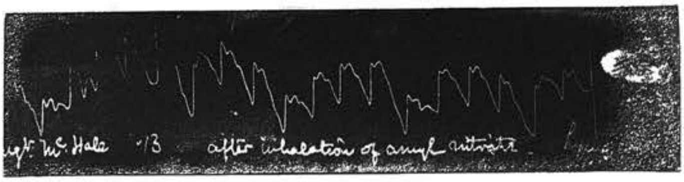

Fig.35.

Figs.34 and 35. Photographs of fontanelle tracings from girl, M.McH., aged 13 months.

In the first part of fig.34 is a short tracing of the fontanelle when child was lying asleep. In the latter part of fig.34 is the tracing got soon after nitrite of amyl was held before the nose; and in fig.35 the tracing a minute or two afterwards when the child was thoroughly under its influence.

The tendency of the pulse to become katacrotic, and the great influence of respiration on the fontanelle pulse then, are well seen in fig.35.

Taken with Marey's sphygmograph.

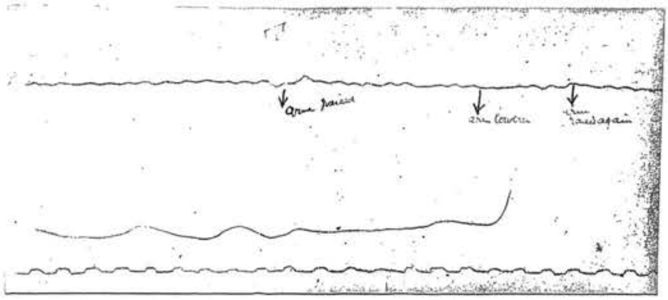

Fig.36. Photograph of fontanelle tracing from girl with persistent fontanelle. Much smaller than original tracing.

A continuous tracing was being taken - at ↓, the arm was raised - immediately there was a rise in the level of the tracing; at ↓2 it was lowered, and the tracing again fell; whilst when raised again at ↓3, it once more rose.

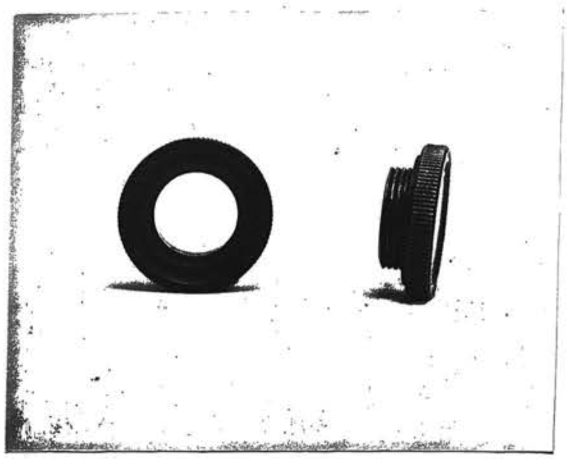

Fig.37. Photograph of the window used in Experiment 5, page . After trephining, and making a thread on the edge of the trephine hole one can

screw in this window and then watch whether any movements of the membranes occur.

A. is the surface view,

B. the side view of the window.